Effects of Intensive Fertilization on the Foliar Nutrition and Growth of Young Lodgepole Pine Forests in the British Columbia Interior: 12-year Results

R.P. Brockley

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ABSTRACT

The effects of different regimes and frequencies of repeated fertilization on the foliar nutrition and growth of young lodgepole pine were investigated at five locations in central British Columbia. When applied at 6-year intervals to 9- to 15-year-old stands, two applications of nitrogen (totalling 400 kg N/ha), with and without other added nutrients, produced 12-year relative stand volume increments that were 7–36% higher than control values. In absolute terms, fertilized stand volume gains ranged from 8.5 to 17.2 m^3/ha over 12 years. Yearly applications of N and other nutrients produced variable results, with 12-year relative stand volume increments ranging from 16% lower (-19.5 m^3/ha) to 60% higher (22.8 m^3/ha) than control values. Poor radial and height increment in some intensively fertilized treatment plots was typically associated with foliar nutrient imbalances (e.g., N/Cu, N/Mg) and lower growth efficiency (i.e., wood production per unit of leaf area). Overall, the 12-year results indicate that yearly nutrient additions are relatively ineffective and inefficient in stimulating the growth of young lodgepole pine. However, periodic application of balanced fertilizers to healthy, nutrient-deficient stands may be a viable strategy for increasing fibre yield, reducing rotation length, and sequestering carbon in managed lodgepole pine forests.

PREFACE

Experimental Project (E.P.) 886.13 *Maximizing the Productivity of Lodgepole Pine and Spruce in the Interior of British Columbia* was implemented by the British Columbia Ministry of Forests Research Branch in 1992 to examine the potential to improve the productivity of interior forests by permanently alleviating nutritional growth constraints. Research with *Pinus* and *Picea* species in other forest regions has indicated that sustained growth responses and large reductions in rotation length are achievable by repeatedly fertilizing young conifer stands. Similar productivity gains in young lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and interior spruce (*Picea glauca* [Moench] Voss, *Picea engelmannii* Parry, and their naturally occurring hybrids) sub-boreal forests would be of great benefit in addressing future timber supply challenges in the British Columbia Interior. Eight area-based field installations (five pine and three spruce) were established on representative sites within three biogeoclimatic zones between 1992 and 1999.

The growth and yield objectives of the "maximum productivity" study are to compare the effects of different regimes and frequencies of repeated fertilization on forest growth and development and to determine optimum fertilization regimes for maximizing stand volume production. In addition, several companion studies have been undertaken at selected sites to determine the long-term effects of large nutrient additions on above- and below-ground timber and non-timber forest resources.

The purpose of this report is to examine the effects of repeated fertilization on foliar nutrition and tree- and stand-level growth and development over 12 years at the five lodgepole pine study sites.

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Nitrogen (N) deficiencies are widespread in young forests throughout the British Columbia (B.C.) Interior, and a single N fertilization often has a substantial positive effect on the growth of several conifer species (Weetman et al. 1988; Brockley 1991, 1992, 1996, 2006). Other nutrient deficiencies may be either induced or aggravated by N fertilization, and growth responses are often enhanced if sulphur (S) and/or boron (B) is combined with N in fertilizer prescriptions (Brockley 2000, 2003, 2004). Because fertilization is a proven method for accelerating the development of established stands, it may be a valuable tool for mitigating the effects of catastrophic mortality losses due to the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) on the amount and timing of future timber supplies. Large-scale aerial fertilizer operations have recently been undertaken in several interior forest management units.

A single fertilizer application typically only temporarily increases tree and stand growth rates (usually 5–10 years) (Binkley 1986). However, fertilization research with *Pinus* and *Picea* species in other forest regions has indicated that sustained growth responses and large reductions in rotation length are achievable by repeatedly fertilizing young stands (Albaugh et al. 2004; Bergh et al. 2005; Ringrose and Neilsen 2005; Högberg et al. 2006). Previous studies have also shown that repeated fertilization of boreal forests increased above- and below-ground carbon (C) sequestration (Iivonen et al. 2006; Hyvönen et al. 2008). Larger C stocks in repeatedly fertilized forests may mitigate the harmful effects of greenhouse gas emissions on the earth's climate and provide valuable greenhouse gas offsets in an emerging global C economy.

Accelerated development of young lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) and interior spruce (white spruce, *Picea glauca* [Moench] Voss; Engelmann spruce, *Picea engelmannii* Parry; and their hybrids) sub-boreal forests would be of great benefit in addressing future timber supply challenges in the British Columbia Interior. However, the effects of repeated fertilization on growth and development of these species must be quantified so that the potential impacts on future timber supply can be evaluated. The impacts of large nutrient additions on other forest resources (e.g., soils, understorey vegetation) and on ecosystem health and sustainability must also be documented.

Beginning in 1992, the British Columbia Ministry of Forests established a small network of lodgepole pine and interior spruce nutrient optimization research installations (E.P. 886.13) on representative sites within three major biogeoclimatic (BEC) zones in the British Columbia Interior. The objectives of the long-term "maximum productivity" study are to (1) compare the effects of different regimes and frequencies of repeated fertilization on the foliar nutrition, growth, and development of young interior forests, and (2) determine the effects of large nutrient additions on above- and below-ground timber and non-timber resources.

This report examines the effects of repeated fertilization on foliar nutrition and tree- and stand-level growth and development over 12 years at the five lodgepole pine study sites. The 12-year results from the three spruce study sites will be reported separately. Early results for the pine and spruce trials were reported by Brockley and Simpson (2004).

2.1 Location, Site, and Stand Descriptions

Five lodgepole pine "maximum productivity" installations were established in 9- to 15-year-old plantations and juvenile-spaced, harvest-origin stands between 1992 and 1996.[1] Three of the installations were established in three different subzones of the Sub-Boreal Spruce (SBS) BEC zone (Meidinger and Pojar 1991), representing a broad range of climatic conditions. The other two installations were established in the Engelmann Spruce–Subalpine Fir (ESSF) and Montane Spruce (MS) BEC zones (Meidinger and Pojar 1991).

The location, site, and stand characteristics of the individual study sites are described in Table 1. Detailed stand and site descriptions of each site are provided below.

2.1.1 Sheridan Creek The Sheridan Creek installation is located 7.5 km east of McLeese Lake, B.C. within the Blackwater variant of the dry warm subzone of the Sub-Boreal Spruce BEC zone (SBSdw2). Soil and vegetation description indicates the site belongs to the zonal SxwFd – Pinegrass (01) site series (Steen and Coupé 1997). The site occurs on a moderately well-drained, gently undulating morainal blanket. The rooting zone has a loamy texture with about 25% volume of gravel and cobbles of acidic, igneous intrusive lithology. There is a root-restricting layer at 35 cm, below which the texture is more clay rich with more coarse fragments. The soil is classified as a Brunisolic Gray Luvisol (Soil Classification Working Group 1998). The site is occupied by a naturally regenerated lodgepole pine stand that originated from a 1978 clearcut and subsequent drag scarification. At the time of installation establishment in 1992, the 13-year-old stand had an average stand density of 20,000 stems per hectare (sph). All treatment plots were thinned to a uniform density of 1100 sph at the time of installation establishment.

2.1.2 Kenneth Creek The Kenneth Creek installation is located approximately 75 km east of Prince George, B.C. within the Willow variant of the wet cool subzone of the Sub-Boreal Spruce BEC zone (SBSwk1). Soil and vegetation description indicates the site belongs to the submesic Sxw – Huckleberry – Highbush-cranberry (05) site series (DeLong 2003). The soil is well drained and stone free and is derived from thick, well-sorted glaciofluvial outwash parent material with a fine to medium loamy sand texture. Although distinct Ae and Bf horizons are evident, the latter horizon is too thin to meet the requirements of the Podzolic order. The soil is classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998). After clearcutting and broadcast burning, the site was planted in the spring of 1983 with lodgepole pine 1+0 container stock. The plantation was chemically brushed in 1986. At the time of installation establishment in 1993, the stand was 12 years old and had an average density of approximately 1360 sph.

2.1.3 McKendrick Pass The McKendrick Pass installation is located approximately 23 km north of Smithers, B.C. within the moist cold subzone of the Engelmann Spruce – Subalpine Fir BEC zone (ESSFmc). Soil and vegetation description indicates that mid- and lower slope positions belong to the zonal

1 Another pine installation was abandoned shortly after establishment due to severe stem damage caused by red squirrel (*Tamiasciurus hudsonicus* Erxleben) feeding injuries.

TABLE 1 *Site and stand descriptions*

Install. No.	Location	Forest District	Latitude	Longitude	Stand origin[a]	Year established	Age @ establishment	BEC subzone	Site series	SI50 (m)[b]	Initial height (m)
1	Sheridan Creek	Central Cariboo	52° 25'	122° 11'	N	1992	13	SBSdw2	01	21.0	4.2
2	Kenneth Creek	Prince George	53° 49'	121° 47'	P	1993	12	SBSwk1	05	21.0	5.6
4	McKendrick Pass	Skeena Stikine	54° 49'	126° 48'	P	1995	9	ESSFmc	01,04	16.2	2.5
6	Tutu Creek	Mackenzie	55° 27'	123° 12'	P	1995	10	SBSmk2	04	18.0	3.7
7	Crater Lake	Quesnel	52° 50'	123° 44'	N	1996	15	MSxv	01,04	18.0	4.0

[a] P = Planted, N = Natural

[b] Site index estimates by Site Series (SIBEC) – second approximation (www.for.gov.bc.ca/hre/sibec)

Bl – Huckleberry – Leafy liverwort (01) site series (Banner et al. 1993). The soils at these slope positions are derived from morainal material and are relatively stone free at the surface with 30–40% gravels and cobbles at depths greater than 15 cm. The upper portions of the site are slightly drier and likely belong to the submesic Bl – Huckleberry – Heron's-bill (04) site series. Soils at upper slope positions are partially derived from colluvial material and have a higher percentage of coarse fragments. Soils at all slope positions are morphologically consistent with Orthic Humo-Ferric Podzols (Soil Classification Working Group 1998). The site was clearcut harvested in 1987 and subsequently broadcast burned. In June 1988, the site was planted with lodgepole pine 1+0 container stock. At the time of installation establishment in 1995, the stand was 9 years old and had an average density of approximately 1200 sph.

2.1.4 Tutu Creek The Tutu Creek installation is located approximately 15 km north of Mackenzie, B.C. within the Williston variant of the moist cool subzone of the Sub-Boreal Spruce BEC zone (SBSmk2). Soil and vegetation description indicates the site belongs to the submesic Sb – Huckleberry – Spirea (04) site series (DeLong 2004). Derived from well-sorted glaciofluvial outwash parent material, the soil is well drained with a medium sandy loam texture and approximately 60% coarse fragments consisting mainly of gravels. Although distinct Ae and Bf horizons are evident, the latter horizon is too thin to meet the requirements of the Podzolic order. The soil is tentatively classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998). The previous stand was clearcut harvested in 1985 and broadcast burned in 1986. The site was planted in the spring of 1987 with lodgepole pine 1+0 container stock. The plantation was mechanically brushed in 1992. At the time of installation establishment in 1995, the stand was 10 years old and had an average density of approximately 1230 sph. Trees in all treatment plots were attacked by the mountain pine beetle in August 2007, two months prior to the 12 year remeasurement.

2.1.5 Crater Lake The Crater Lake installation is located approximately 85 km west of Quesnel, B.C. within the very dry very cold subzone of the Montane Spruce BEC zone (MSxv). Depending on slope position, soil and vegetation description indicates the site belongs to two site series—the submesic Pl – Grouseberry – Kinnikinnick (04) site series and the zonal Pl – Grouseberry – Feathermoss (01) site series (Steen and Coupé 1997). The soil is derived from morainal parent material and is well drained with a sandy loam texture and 60% coarse fragments (mainly gravel and cobbles). The soil is classified as an Eluviated Dystric Brunisol (Soil Classification Working Group 1998). The previous stand was clearcut harvested in 1978 and chain dragged in the fall of 1979. Landings were burned in the fall of 1980, and escapes from these fires lightly burned portions of the surrounding cutblock. The naturally regenerated lodgepole pine stand was juvenile spaced in 1995. At the time of installation establishment in 1996, the stand was approximately 15 years old and had an average density of approximately 2000 sph.

2.2 Study Establishment

Six treatments were tested as follows: (1) control (i.e., not fertilized); (2) NB: fertilize every 6 years with 200 kg N/ha (200N) and 1.5 kg B/ha (1.5B); (3) NSB: fertilize every 6 years with 200N, 50 kg S/ha (50S), and 1.5B; (4) complete: fertilize every 6 years with 200N, 100 kg phosphorus (P)/ha (100P),

100 kg potassium (K)/ha (100K), 50S, 25 kg magnesium (Mg)/ha (25Mg), and 1.5B; (5) optimum nutrition 1 (ON_1): yearly fertilization to maintain foliar N concentration at 1.3% and other nutrients in balance with foliar N; and (6) optimum nutrition 2 (ON_2): yearly fertilization to maintain foliar N concentration at 1.6% and other nutrients in balance with foliar N.

Boron was added to the NB, NSB, and complete treatments to safeguard against the possibility of B deficiencies induced by repeated N additions. Foliar B levels are characteristically low in lodgepole pine forests throughout central British Columbia (Brockley 2003). The NSB and complete treatments were included to test for incremental growth responses attributable to S and other added nutrients.

The ON_1 and ON_2 treatments were patterned after "optimum nutrition" experiments in Sweden (Tamm 1991; Tamm et al. 1999) and Canada (Weetman et al. 1995; Kishchuk et al. 2002). The ON_1 and ON_2 treatment plots typically received 50–100 kg N/ha and 100–200 kg N/ha, respectively, each spring. Other nutrients (e.g., P, K, Mg, S, and B) were added periodically to provide an appropriate nutrient balance and to minimize growth limitations caused by secondary deficiencies. Yearly fertilizer prescriptions for ON_1 and ON_2 treatments at each study site were developed following foliar sampling and nutrient analysis each fall. Individual nutrients for customized blends were included in amounts and frequencies that were deemed necessary to achieve foliar N targets and to keep nutrient ratios (e.g., N/P, N/K, N/S, and N/Mg) below published critical thresholds (Ingestad 1979; Linder 1995; Braekke and Salih 2002). Specifically, the selected thresholds for foliar nutrient ratios were as follows: N/P, 10; N/K, 3; N/S, 15; N/Mg, 20; N/Ca, 20; N/B, 1000; and N/Cu, 7500.

Each of the six treatments was assigned to three 0.164-ha (45.3 m × 36.2 m) treatment plots at each study site. Each treatment plot consisted of an inner square 0.058-ha (24 m × 24 m) assessment plot surrounded by a treated buffer. Three sides of the assessment plot were surrounded by a 6.04-m buffer; the enlarged buffer on the fourth side (15.1 m) provided an area for future destructive sampling. Each treatment plot contained approximately 180 crop trees, equivalent to a stand density of 1100 sph at 3-m square spacing. Growth analyses for each plot were based on periodic measurement of 64 permanently tagged trees within the inner assessment plot. Surplus trees within the assessment plot and buffer were selected and felled at the time of plot establishment.

Treatment plots were systematically located so that within- and between-plot conditions (e.g., stand density, tree height, tree diameter at breast height (dbh), soil characteristics, and minor vegetation) were as uniform as possible. The outer boundaries of adjacent treatment plots were separated by a minimum distance of 5 m. A minimum distance of 20 m separated the outer treatment plot boundaries from roads or large stand openings.

At two study sites (Kenneth Creek and Tutu Creek), each of the six treatments was randomly assigned to three of the plots (i.e., completely randomized experimental design). At the three other sites (Sheridan Creek, McKendrick Pass, and Crater Lake), geographic separation of plots or possible site differences (e.g., slope position) dictated a randomized complete block experimental design. In these cases, treatment plots were grouped into three blocks (six plots per block) such that site and stand conditions were as uniform as possible within each block (e.g., upper, middle, lower slope posi-

tions). Each of the six treatments was randomly assigned to one plot within each block.

2.3 Foliar Sampling and Analysis

Current year's foliage was collected from the upper one-third of the live crown of 10 codominant or dominant trees in control, ON_1, and ON_2 treatment plots each fall (late September to late October). For all other treatments (NB, NSB, and complete), foliage was collected in the fall prior to the initial fertilization (year 0) and after the 1st, 6th, 7th (1st year after refertilization), and 12th year (foliage was not collected at Tutu Creek in year 12 due to mountain pine beetle attack). Detailed foliar sampling methodology is described in Brockley and Simpson (2004).

Foliage collected prior to 2000 was sent to a commercial laboratory for nutrient analysis. Subsequent analyses were undertaken by the British Columbia Ministry of Forests and Range laboratory. Nutrient extraction and determination methodology is fully described in Brockley and Simpson (2004). Foliar N and S levels were affected by inter-laboratory differences in analytical methodology. Methods described in Brockley and Simpson (2004) were used to "normalize" foliar N and S values obtained from the Ministry of Forests and Range laboratory and thus facilitate year-to-year comparisons of foliar nutrient data.

2.4 Fertilization

The NB treatment was a customized combination of urea (46–0–0; N–P–K) and granular borate (15% B) blended to deliver 200N and 1.5B. In the NSB treatment, urea, ammonium sulphate (21–0–0–24; N–P–K–S) and granular borate were combined to deliver 200N, 50S, and 1.5B. In the complete treatment, urea was the major source of N. A small amount of N (24% of the total) was added as monoammonium phosphate (11–52–0; N–P–K), which also served as the P source. Potassium was delivered as potassium chloride (0–0–60; N–P–K) and sulphate potash magnesia (0–0–22–22–11; N–P–K–S–Mg). The latter fertilizer was also the source of S and Mg. Boron was added as granular borate. The individual sources were combined to deliver 200N, 100P, 100K, 50S, 25Mg, and 1.5B.

Urea was the primary N source for the ON_1 and ON_2 treatments. Additional sources of N were monoammonium phosphate and ammonium nitrate (34–0–0; N–P–K). Phosphorus was always added as monoammonium phosphate. Sulphate potash magnesia was used extensively as a source of K, S, and Mg. Potassium chloride, ammonium sulphate, and ProMag 36 (36% Mg) were used to supply additional K, S, and Mg, respectively. Boron was supplied as granular borate.

All NB, NSB, and complete treatment plots were fertilized in the spring (after snowmelt) following study establishment and were refertilized in the spring following the 6th growing season. Customized fertilizer blends were applied to the ON_1 and ON_2 treatment plots each spring for 12 years. A premeasured amount of each fertilizer was uniformly broadcast applied by hand to each treatment plot.

Complete fertilization histories for each of the five pine study sites from the time of establishment (year 0) through year 12 are shown in Appendices 1–5.

2.5 Tree Growth

At each study site, dbh, total height, and tree form and condition of all 64 trees within each assessment plot were measured at the time of establishment and every 3 years thereafter. Tree crown width (i.e., the vertically projected

maximum horizontal distance between opposite crown margins) was measured in year 12.

Diameter measurements were taken with a steel diameter tape at a permanently marked point approximately 130 cm above the ground. A telescoping height pole was used for initial tree height measurements. Subsequent height measurements were taken with a Forestor Vertex® hypsometer. Crown width was measured in two directions (at right angles) with a steel measuring tape.

2.6 Leaf Area Index

Beginning in 2002, the development of stand leaf area index (LAI) was monitored at each study site, with most measurements timed to coincide with scheduled 3-year growth measurements. An indirect estimate of LAI was obtained for each treatment plot in late spring (before bud flush) using a Li-Cor LAI-2000 plant canopy analyzer (Li-Cor, Inc. 1991). Several studies have shown a strong positive correlation, but negative bias (due to tree and stand foliage clumping), between LAI estimates obtained with the LAI-2000 in conifer stands and direct LAI values determined by dimension analysis (Smith et al. 1993).

Six-, 9-, and 12-year LAI measurements were obtained at Crater Lake, and 9- and 12-year measurements were obtained at Sheridan Creek and Kenneth Creek. The scheduled 12-year LAI assessments at McKendrick Pass and Tutu Creek were not undertaken due to staff unavailability. At McKendrick Pass, 6- and 9-year measurements were supplemented with an assessment at year 13. Only 6- and 9-year LAI measurements were obtained from Tutu Creek, since mountain pine beetle damage precluded assessment in year 13.

Measurements were obtained at a height of 80–100 cm above the ground at nine permanently marked points within each treatment plot. Two readings were obtained at each point, one facing northwest and the other facing northeast before and after solar noon, respectively. Sensors were equipped with a 180° view cap. Simultaneously, above-canopy light measurements were collected in an open area adjacent to the study site where the light sensor had an unobstructed view of the sky.

2.7 Data Analysis

Twelve-year basal area (BA), height, and total volume increments, as well as dbh/height ratios, were calculated for all trees alive after 12 years and were analyzed by analysis of covariance (ANCOVA) (SAS Institute Inc. 2004). Initial BA, height, total volume, and dbh/height, respectively, were used as covariates. Using only those trees alive after 12 years, stand BA and volumes were determined for each measurement by summing individual tree values in each plot and converting plot area to a per-hectare basis. The 12-year stand BA and volume increments were analyzed by ANCOVA, with initial stand BA and volume used as covariates. For all variables, the ANCOVA adjusted treatment means are presented. Individual tree total volumes (inside bark) were calculated from a variable-exponent taper function that was developed for lodgepole pine in the Central Interior of British Columbia (Kozak 1988). Calculated stem volumes do not account for possible treatment-related changes in tree taper and form.

The crown width measurements that were obtained at year 12 and the latest LAI measurements (12-year for Sheridan Creek, Kenneth Creek, and Crater Lake; 13-year for McKendrick Pass; 9- year for Tutu Creek) were subjected to ANOVA.

For all analyses, *a priori* single degree of freedom contrasts were used to test for differences between (1) unfertilized and "periodic" fertilizer treatments (control vs. NB, NSB, complete), (2) NB and other "periodic" treatments (NB vs. NSB and complete), (3) "periodic" and "annual" fertilization (NB, NSB, complete vs. ON_1 and ON_2), and (4) the two "annual" treatments (ON_1 vs. ON_2).

A level of significance of $\alpha = 0.05$ is used throughout the text for inferring statistical significance. In each analysis, the combined type I error probability associated with the four pre-planned contrasts may exceed 0.05. To compensate for this possibility, the reader may wish to apply a more stringent level of significance when interpreting the contrasts.

Linear regression was used to quantify the relationship between productivity and light interception. For these analyses, effective LAI (m^2/m^2) and corresponding stand BA (m^2/ha) data for each treatment plot were pooled across all years available. The base relationship was in the form of a simple model:

$$BA = \beta_0 + (\beta_1 \times LAI) \quad (1)$$

where β_0 and β_1 were parameters to be estimated.

In order to understand how fertilizer treatment affected the slope of the BA–LAI relationship, an expanded model was examined as follows:

$$BA = \beta_0 + (\beta_1 \times LAI) + (\beta_2 \times LAI \times F) \quad (2)$$

where BA and LAI were the same as in the base model, β_0, β_1, and β_2 were parameters to be estimated, and F indicated fertilization (0 if non-fertilized and 1 if fertilized). Another expanded model was examined to determine the effects of the periodic (NB, NSB, complete) and annual (ON_1 and ON_2) fertilizer treatments:

$$BA = \beta_0 + (\beta_1 \times LAI) + (\beta_2 \times LAI \times \text{periodic}) + (\beta_3 \times LAI \times ON_1) + (\beta_4 \times LAI \times ON_2) \quad (3)$$

where periodic (NB, NSB, complete), ON_1, and ON_2 indicated treatment (0 if not applicable and 1 if applicable).

3 RESULTS

3.1 Foliar Nitrogen

3.1.1 Yearly fertilization (ON_1 and ON_2) Pre-fertilization foliar N concentration was between 1.1 and 1.2% at all study sites (Figure 1).* Foliar N levels in control plots at each site fluctuated during the 12-year observation period but generally remained below 1.2%. In contrast, foliar N concentrations in ON_1 and ON_2 treatment plots increased following the initial fertilizer application, and remained higher than control N levels through year 12 (Figure 1). The different rates of yearly fertilization created distinct separation between the foliar N levels in the control, ON_1, and ON_2 treatments at most sites. However, foliar N concentrations in the ON_1 and ON_2 treatments at several sites remained below target values (1.3% and 1.6%, respectively) during much of the 12-year study period.

* Figures 1–25 are on pages 16–40.

3.1.2 Periodic fertilization (NB, NSB, complete) Foliar N levels increased in the 1st year after the initial application of NB, NSB, and complete fertilizers at all study sites (Figure 2). However, foliar N levels in most periodic treatments were at or below control levels after 6 years. Foliar N also increased in NB, NSB, and complete treatments in the year following refertilization (year 7) (Figure 2). However, foliar N levels in most fertilized treatments were lower in year 7 than in year 1 at four of the five sites. As with the initial fertilization, foliar N levels in most fertilized treatments were at or below control levels by year 12.

3.2 Foliar Nutrient Balance

3.2.1 Yearly fertilization (ON_1 and ON_2) Periodic inclusion of P, K, and S in ON_1 and ON_2 fertilizer regimes generally maintained absolute foliar concentrations of these nutrients at or above pre-treatment levels (data not shown). Consequently, favourable balances between N and these added nutrients were maintained at most lodgepole pine sites (Figures 3–5). However, foliar N/P, N/K, and N/S ratios in the ON_2 treatment sometimes rose above critical thresholds at Kenneth Creek (Figures 3b, 4b, 5b). Foliar N/K and N/S thresholds were, at times, slightly exceeded at Sheridan Creek and McKendrick Pass, respectively (Figures 4a and 5c).

Foliar N/B levels were close to threshold values at the time of establishment at most study sites (Figure 6). The N/B levels in control treatments generally remained near or above the threshold value in subsequent years. Periodic boron additions to ON_1 and ON_2 treatments reduced foliar N/B ratios at all sites.

Despite the inclusion of small amounts of Mg in fertilizer prescriptions, foliar N/Mg ratios in ON_1 and ON_2 treatments exceeded threshold values for 2–4 years shortly after trial establishment at four study sties (Figure 7). Favourable N/Mg balance was restored at all sites following additions of larger quantities of Mg-containing fertilizers (Appendices 1–5).

Foliar N/Cu ratios in the ON_2 treatment exceeded the threshold value for prolonged periods at Kenneth Creek, McKendrick Pass, and Tutu Creek (Figure 8). Supplemental Cu additions were apparently temporarily effective at improving foliar Cu levels, but N/Cu ratios remained above threshold values at these three sites.

Calcium was not included in ON_1 and ON_2 fertilizer prescriptions. Consequently, foliar N/Ca ratios increased following fertilization, and remained higher than control values throughout the 12-year study period (Figure 9). However, N/Ca ratios always remained below the threshold value in all installations.

3.2.2 Periodic fertilization (NB, NSB, complete) Foliar N/P, N/K, and N/Mg ratios increased following fertilization (year 1) and refertilization (year 7) with NB, NSB, and complete fertilizers at most study sites (Figures 10–12). Ratios temporarily approached or exceeded threshold values at several sites, but more favourable nutrient balance was restored by years 6 and 12. Foliar N/Cu ratios also increased following periodic fertilization, especially after refertilization in year 7 (Figure 13). However, N/Cu ratios did not approach threshold values at any of the study sites.

Foliar N/S ratios in NB treatments slightly exceeded threshold values following initial fertilization at three study sites (Figure 14). Added S was effective in maintaining favourable N/S balance after initial application of

NSB and complete fertilizers. Interestingly, foliar N/S levels in the year following refertilization (year 7) were almost always higher than those observed after initial fertilization (year 1) (Figure 14).* For NB treatments, the elevated foliar N/S ratios following refertilization exceeded the threshold value at several study sites but declined to more favourable levels by year 12.

The B included in periodic fertilizer treatments almost always reduced foliar N/B ratios compared to ratios in unfertilized foliage (Figure 15). Except for 1st year results at McKendrick Pass, foliar N/B ratios remained below the threshold value in all periodic treatments.

3.3 Individual Tree Growth

Fertilization had a significant effect on height increment at all five study sites (Table 2). Periodic fertilization (every 6 years) resulted in significantly larger 12-year height increments compared to unfertilized trees at Sheridan Creek and Crater Lake (Table 2; Figure 16a, e). However, absolute height increases from two applications of NB, NSB, and complete fertilizers were quite small (23–48 cm) at these two sites. Except at Crater Lake, fertilization with NSB and complete fertilizers did not result in significantly more height increment than did fertilization with NB (Table 2; Figure 16e). There was significantly less height increment associated with yearly fertilization than with periodic fertilization at Sheridan Creek, Kenneth Creek, and McKendrick Pass (Table 2; Figure 16a, b, c). At these three sites (and at Tutu Creek), negative 12-year height increments relative to the control were observed in ON_2 treatment plots (Figure 16a–d). This effect was most pronounced at Kenneth Creek, where reductions in height increment of ON_2-fertilized trees compared to unfertilized trees totalled 1.7 m over 12 years.

The effects of fertilization on mean 12-year tree BA and volume increment are shown in Table 2 and Figures 17 and 18. Except for Kenneth Creek, periodic applications of NB, NSB, and complete fertilizers resulted in significantly more tree BA and volume increment compared to the control treatment over 12 years. Among periodic treatments, repeated applications of NSB and complete fertilizers were significantly more effective than NB in stimulating BA growth at Sheridan Creek and Kenneth Creek (Table 2; Figure 17a, b). Yearly nutrient additions (ON_1 and ON_2) resulted in significantly more BA increment than did periodic application of NB, NSB, and complete fertilizers at four of the study sites (Table 2; Figure 17). Conversely, yearly fertilization resulted in significantly less 12-year BA increment than did periodic fertilization at Kenneth Creek (Table 2; Figure 17b). The ON_2-fertilized trees had significantly more BA growth than did trees in the ON_1 treatment at McKendrick Pass, Tutu Creek, and Crater Lake (Table 2; Figure 17c–e). Tree volume increments showed similar trends (Table 2; Figure 18). Tree volume growth in the ON_2 treatment at Kenneth Creek was distinctly negative relative to the control treatment, especially during the 7- to 12-year response period (Figure 18b).

After 12 years, trees fertilized twice with NB, NSB, and complete fertilizers had significantly larger dbh/height ratio than did unfertilized trees at all five sites (Table 2; Figure 19). Ratios were significantly larger in NSB and complete treatments than in the NB treatment at Sheridan Creek and Kenneth Creek (Table 2; Figure 19a, b). Yearly fertilization resulted in significantly larger dbh/height ratio than did periodic fertilization at all five sites (Table 2; Figure 19). Differences between ON_1 and ON_2 treatments were also statistically sig-

* Figures 1–25 are on pages 16–40.

TABLE 2 *ANCOVA summary table for 12-year tree height increment (m), basal area increment (cm^2), volume increment (dm^3), and diameter at breast height (dbh)/height ratio (cm/m) showing observed F statistics, probability (p) values, and error mean squares*

		Height increment		Basal area increment		Volume increment		dbh/height ratio	
Source of variation	**df**	*F*	*p>F*	*F*	*p>F*	*F*	*p>F*	*F*	*p>F*
Sheridan Creek									
Treatment	5	4.16	0.026	23.07	<0.001	12.56	<0.001	28.86	<0.001
Control vs. periodic	1	5.50	0.041	47.99	<0.001	34.20	<0.001	25.12	<0.001
NB vs. NSB and complete	1	0.19	0.674	14.81	0.003	8.38	0.016	12.34	0.006
Periodic vs. annual	1	8.66	0.015	19.17	0.001	4.40	0.062	52.71	<0.001
ON1 vs. ON2	1	7.97	0.018	0.06	0.808	1.92	0.196	7.23	0.023
Covariate	1	1.11	0.317	278.84	<0.001	322.79	<0.001	160.26	<0.001
Error mean square	10	2.78		1902.63		692.25		0.047	
Kenneth Creek									
Treatment	5	9.37	<0.001	2.97	0.057	4.61	0.014	11.60	<0.001
Control vs. periodic	1	0.85	0.376	4.03	0.068	1.35	0.268	13.90	0.003
NB vs. NSB and complete	1	0.01	0.921	5.19	0.042	2.54	0.137	5.01	0.045
Periodic vs. annual	1	19.90	<0.001	6.18	0.029	12.62	0.004	11.16	0.006
ON1 vs. ON2	1	22.27	<0.001	1.81	0.203	8.50	0.013	16.41	0.002
Covariate	1	2.10	0.173	84.70	<0.001	122.79	<0.001	109.34	<0.001
Error mean square	12	7.22		9881.67		5659.68		0.064	
McKendrick Pass									
Treatment	5	7.16	0.004	81.08	<0.001	22.83	<0.001	70.77	<0.001
Control vs. periodic	1	0.49	0.500	125.28	<0.001	52.91	<0.001	49.70	<0.001
NB vs. NSB and complete	1	0.00	0.956	3.12	0.108	0.96	0.350	2.95	0.116
Periodic vs. annual	1	18.03	0.002	145.58	<0.001	26.00	<0.001	164.46	<0.001
ON1 vs. ON2	1	18.09	0.002	11.75	0.006	0.07	0.791	56.46	<0.001
Covariate	1	2.48	0.146	455.22	<0.001	360.42	<0.001	69.46	<0.001
Error mean square	10	1.36		1104.53		331.05		0.077	
Tutu Creek									
Treatment	5	5.22	0.009	18.05	<0.001	11.52	<0.001	25.20	<0.001
Control vs. periodic	1	0.60	0.452	29.52	<0.001	25.22	<0.001	25.30	<0.001
NB vs. NSB and complete	1	0.93	0.353	2.46	0.143	0.89	0.363	3.56	0.083
Periodic vs. annual	1	4.46	0.056	26.35	<0.001	13.54	0.003	38.01	<0.001
ON1 vs. ON2	1	19.97	<0.001	6.09	0.030	0.40	0.538	32.32	<0.001
Covariate	1	0.17	0.687	130.58	<0.001	221.37	<0.001	68.62	<0.001
Error mean square	12	1.27		3564.58		783.80		0.086	
Crater Lake									
Treatment	5	3.38	0.048	35.66	<0.001	24.06	<0.001	14.68	<0.001
Control vs. periodic	1	6.14	0.033	35.23	<0.001	28.35	<0.001	8.29	0.016
NB vs. NSB and complete	1	6.00	0.034	0.24	0.636	1.94	0.194	3.43	0.094
Periodic vs. annual	1	0.75	0.405	87.38	<0.001	54.17	<0.001	36.97	<0.001
ON1 vs. ON2	1	1.82	0.207	6.15	0.033	1.42	0.260	7.65	0.020
Covariate	1	0.80	0.392	398.25	<0.001	517.59	<0.001	145.25	<0.001
Error mean square	10	2.10		1899.55		430.29		0.118	

nificant at all sites, with the largest dbh/height ratio always associated with the most intensive fertilization treatment.

3.4 Stand Growth

Periodic fertilization resulted in significantly larger 12-year stand BA increment compared to the unfertilized treatment at all five study sites (Table 3; Figure 20).* Averaged for all sites, relative BA gains in the NB, NSB, and complete treatments were 16%, 21%, and 23%, respectively. Only at Sheridan Creek was BA increment significantly larger in NSB and complete treatments than in the NB treatment (Table 3; Figure 20a). Yearly fertilization (ON_1 and ON_2) resulted in significantly more BA increment than did periodic fertilization at four study sites (Table 3; Figure 20). Conversely, 12-year BA increment was significantly lower in ON_1 and ON_2 treatments than in periodic treatments at Kenneth Creek (Table 3; Figure 20b).

Mean 12-year stand total volume increment was significantly affected by treatment at all five study sites (Table 3; Figure 21). Except for Kenneth Creek, stand volume gains from two applications of NB, NSB, and complete fertilizers were significantly larger than those in the unfertilized treatment. Averaged for all five sites, volume increments in the NB, NSB, and complete treatments were 11.0 m^3/ha (range 8.5–16.0), 13.5 m^3/ha (range 11.9–14.4), and 13.2 m^3/ha (range 10.7–17.2), respectively, greater than those in the control treatment over 12 years. The corresponding relative gains were 17% (7–27%), 21% (12–31%), and 20% (10–36%). Differences between periodic treatments were not statistically significant at any of the study sites. Yearly nutrient additions (ON_1 and ON_2) resulted in significantly greater volume increment than did periodic fertilization at McKendrick Pass and Crater Lake (Table 3; Figure 21c, e). Conversely, yearly fertilization resulted in significantly less stand volume increment than did periodic fertilization at Kenneth Creek over 12 years (Table 3; Figure 21b). Averaged for all five sites, mean total volume increments in the ON_1 and ON_2 treatments were 18.0 m^3/ha (range 9.5–21.0 m^3/ha) and 10.2 m^3/ha (range -19.5–22.8 m^3/ha), respectively, greater than in the control treatment over 12 years. The corresponding mean 12-year relative volume gains were 28% (range 8–52%) and 16% (range -16–60%), respectively. The 12-year stand volume increment in the ON_2 treatment was significantly smaller than in the ON_1 treatment at Kenneth Creek (Table 3; Figure 21b). Although not statistically significant, a similar trend was evident at three other sites (Figure 21).

3.5 Crown Characteristics

Mean crown width at year 12 was significantly affected by treatment at three of the five sites (Table 4; Figure 22). At Sheridan Creek, McKendrick Pass, and Crater Lake, the crowns of trees that were periodically fertilized with NB, NSB, or complete fertilizers were significantly wider than the crowns of unfertilized trees after 12 years (Table 4; Figure 22a, c, e). In no case were differences between the three periodic treatments statistically significant (Table 4). Yearly fertilization (ON_1 and ON_2) resulted in significantly wider tree crowns than did periodic fertilization at Sheridan Creek, McKendrick Pass, and Crater Lake (Table 4; Figure 22). Differences between ON_1 and ON_2 treatments were statistically significant only at Crater Lake, where the largest crown width was associated with the largest nutrient inputs (Table 4; Figure 22e).

* Figures 1–25 are on pages 16–40.

TABLE 3 *ANCOVA summary table for 12-year stand basal area increment (m^2/ha) and volume increment (m^3/ha) showing observed F statistics, probability (p) values, and error mean squares.*

Source of variation	df	Basal area increment		Volume increment	
		F	*p>F*	*F*	*p>F*
Sheridan Creek					
Treatment	5	15.42	<0.001	8.17	0.004
Control vs. periodic	1	34.62	<0.001	23.19	<0.001
NB vs. NSB and complete	1	6.78	0.029	4.02	0.076
Periodic vs. annual	1	11.06	0.009	1.82	0.210
ON1 vs. ON2	1	0.92	0.364	2.84	0.126
Covariate	1	7.44	0.023	8.19	0.019
Error mean square	9	0.445		17.476	
Kenneth Creek					
Treatment	5	5.11	0.011	6.62	0.004
Control vs. periodic	1	10.61	0.008	4.02	0.070
NB vs. NSB and complete	1	1.80	0.207	0.55	0.473
Periodic vs. annual	1	7.97	0.017	12.64	0.004
ON1 vs. ON2	1	7.79	0.017	16.88	0.002
Covariate	1	0.00	0.993	0.58	0.462
Error mean square	11	1.165		71.949	
McKendrick Pass					
Treatment	5	51.30	<0.001	19.04	<0.001
Control vs. periodic	1	93.25	<0.001	49.45	<0.001
NB vs. NSB and complete	1	0.98	0.348	0.11	0.744
Periodic vs. annual	1	96.64	<0.001	20.24	0.001
ON1 vs. ON2	1	4.61	0.060	1.03	0.336
Covariate	1	22.95	0.001	16.18	0.003
Error mean square	9	0.280		6.913	
Tutu Creek					
Treatment	5	16.66	<0.001	11.85	<0.001
Control vs. periodic	1	26.76	<0.001	30.05	<0.001
NB vs. NSB and complete	1	0.00	0.954	0.77	0.400
Periodic vs. annual	1	16.61	0.002	4.23	0.064
ON1 vs. ON2	1	1.00	0.339	2.82	0.121
Covariate	1	2.66	0.131	2.29	0.158
Error mean square	11	0.573		11.512	
Crater Lake					
Treatment	5	23.49	<0.001	14.49	<0.001
Control vs. periodic	1	29.32	<0.001	20.73	0.001
NB vs. NSB and complete	1	0.25	0.630	1.64	0.232
Periodic vs. annual	1	69.73	<0.001	38.65	<0.001
ON1 vs. ON2	1	5.05	0.051	0.96	0.352
Covariate	1	9.14	0.014	15.12	0.004
Error mean square	9	0.391		9.313	

TABLE 4 *ANOVA summary table for crown width (m) at year 12 and leaf area index (m^2/m^2) at year 9 (Tutu Creek), year 12 (Sheridan Creek, Kenneth Creek, Crater Lake), and year 13 (McKendrick Pass) showing observed F statistics, probability (p) values, and error mean squares.*

Source of variation	df	Crown width		Leaf area index	
		F	*p>F*	*F*	*p>F*
Sheridan Creek					
Treatment	5	26.30	<0.001	11.71	<0.001
Control vs. periodic	1	30.48	<0.001	2.35	0.156
NB vs. NSB and complete	1	3.02	0.113	1.43	0.259
Periodic vs. annual	1	54.31	< 0.001	38.89	<0.001
ON1 vs. ON2	1	0.02	0.885	4.47	0.060
Error mean square	10	0.790		0.377	
Kenneth Creek					
Treatment	5	0.41	0.835	1.39	0.296
Control vs. periodic	1	0.02	0.900	2.65	0.130
NB vs. NSB and complete	1	0.13	0.721	0.06	0.816
Periodic vs. annual	1	0.85	0.374	0.69	0.422
ON1 vs. ON2	1	0.78	0.394	4.10	0.066
Error mean square	12	12.349		1.112	
McKendrick Pass					
Treatment	5	5.26	0.012	10.91	<0.001
Control vs. periodic	1	5.07	0.048	10.75	0.008
NB vs. NSB and complete	1	2.35	0.156	0.01	0.908
Periodic vs. annual	1	10.74	0.008	27.30	<0.001
ON1 vs. ON2	1	0.42	0.530	0.21	0.657
Error mean square	10	1.201		0.370	
Tutu Creek					
Treatment	5	2.77	0.069	19.07	<0.001
Control vs. periodic	1	4.32	0.060	17.94	0.002
NB vs. NSB and complete	1	0.01	0.937	0.18	0.676
Periodic vs. annual	1	3.64	0.081	41.24	<0.001
ON1 vs. ON2	1	3.39	0.148	10.32	0.007
Error mean square	12	0.871		0.197	
Crater Lake					
Treatment	5	9.15	0.002	17.40	<0.001
Control vs. periodic	1	9.61	0.011	12.22	0.006
NB vs. NSB and complete	1	0.30	0.593	1.31	0.278
Periodic vs. annual	1	17.65	0.002	39.43	<0.001
ON1 vs. ON2	1	5.55	0.041	12.82	0.005
Error mean square	10	3.563		0.422	

The effects of fertilization on LAI are shown in Table 4 and Figure 23. Leaf area index following two applications of NB, NSB, and complete fertilizers was significantly larger than in the unfertilized treatment at three sites (McKendrick Pass, Tutu Creek, and Crater Lake) (Table 4; Figure 23c–e). Differences between periodic treatments were not statistically significant. Except for Kenneth Creek, there was significantly more LAI associated with yearly fertilization than with periodic fertilization (Table 4; Figure 23).* The LAI in the ON_2 treatment was significantly higher than in the ON_1 treatment at Tutu Creek and Crater Lake (Table 4; Figure 23d, e). Although not statistically significant, a similar trend was evident at Sheridan Creek (Table 4; Figure 23a). Conversely, LAI was apparently lower ($p = 0.066$) in the ON_2 treatment than in the ON_1 treatment at Kenneth Creek after 12 years (Figure 23b).

3.6 Growth Efficiency

Based on all available 6-, 9-, and 12-year LAI and BA measurements, there was a strong linear relationship between stand BA and corresponding LAI at four of five study sites (Figure 24). At these sites, 58–91% of the variation in stand BA was accounted for by LAI (Figure 24). Conversely, the relationship between BA and LAI was very weak at Kenneth Creek (Figure 24b). With all sites (excluding Kenneth Creek) combined, 79% of the variation in stand BA was accounted for by differences in LAI (Equation 1 in Table 5). No additional variation in stand BA growth was accounted for by the small positive effect that fertilization (LAI × F) had on the slope of the expanded model (Equation 2). Separating the periodic (NB, NSB, complete), ON_1, and ON_2 fertilizer treatments in the regression model explained an additional 2% of variation in stand BA (Equation 3 in Table 5).

Stand BA growth efficiency (i.e., wood production per unit of leaf area) increased 5% from 4.53 m^2/ha per unit of LAI in control plots to 4.77 m^2/ha per unit of LAI in fertilized plots (Equation 2 in Table 5). As shown in Table 5 (Equation 3) and Figure 25, the periodic and ON_1 treatments both had small positive effects (5 and 7%, respectively) on growth efficiency. Conversely, BA growth efficiency in the ON_2 treatment was 7% lower than in the control treatment (Table 5 and Figure 25).

TABLE 5 *Models used to examine the relationship between stand basal area (BA) and leaf area index (LAI). Summary statistics and parameter estimates are presented.*

Model[a]	Regression equation	n	RMSE[b]	R^2
Base model [Equation (1)]	BA = 3.96 + (4.82 × LAI)	162	1.52	0.79
Expanded model [Equation (2)]	BA = 4.09 + (4.53 × LAI) + (0.24 × LAI × F)	162	1.52	0.79
Expanded model [Equation (3)]	BA = 3.54 + (4.97 × LAI) + (0.26 × LAI × Periodic) + (0.35 × LAI × ON1) − (0.34 × LAI × ON2)	162	1.45	0.81

[a] See text for equation forms, variable definitions, and units.
[b] Root mean square error

* Figures 1–25 are on pages 16–40.

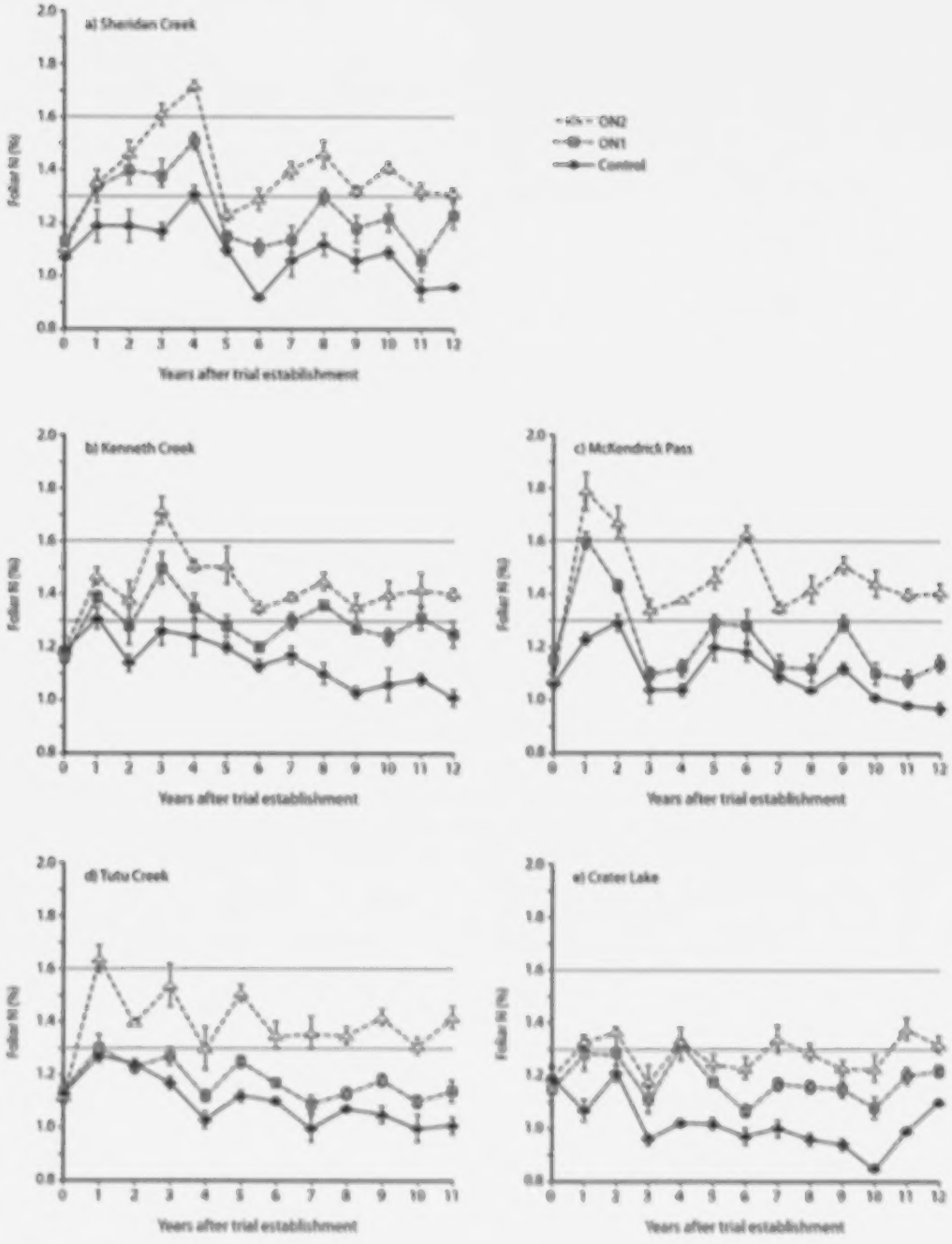

FIGURE 1 *Foliar nitrogen (N) concentration by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). Error bars represent standard error of the mean. The dotted horizontal lines represent the target values for ON1 (1.3%) and ON2 (1.5%).*

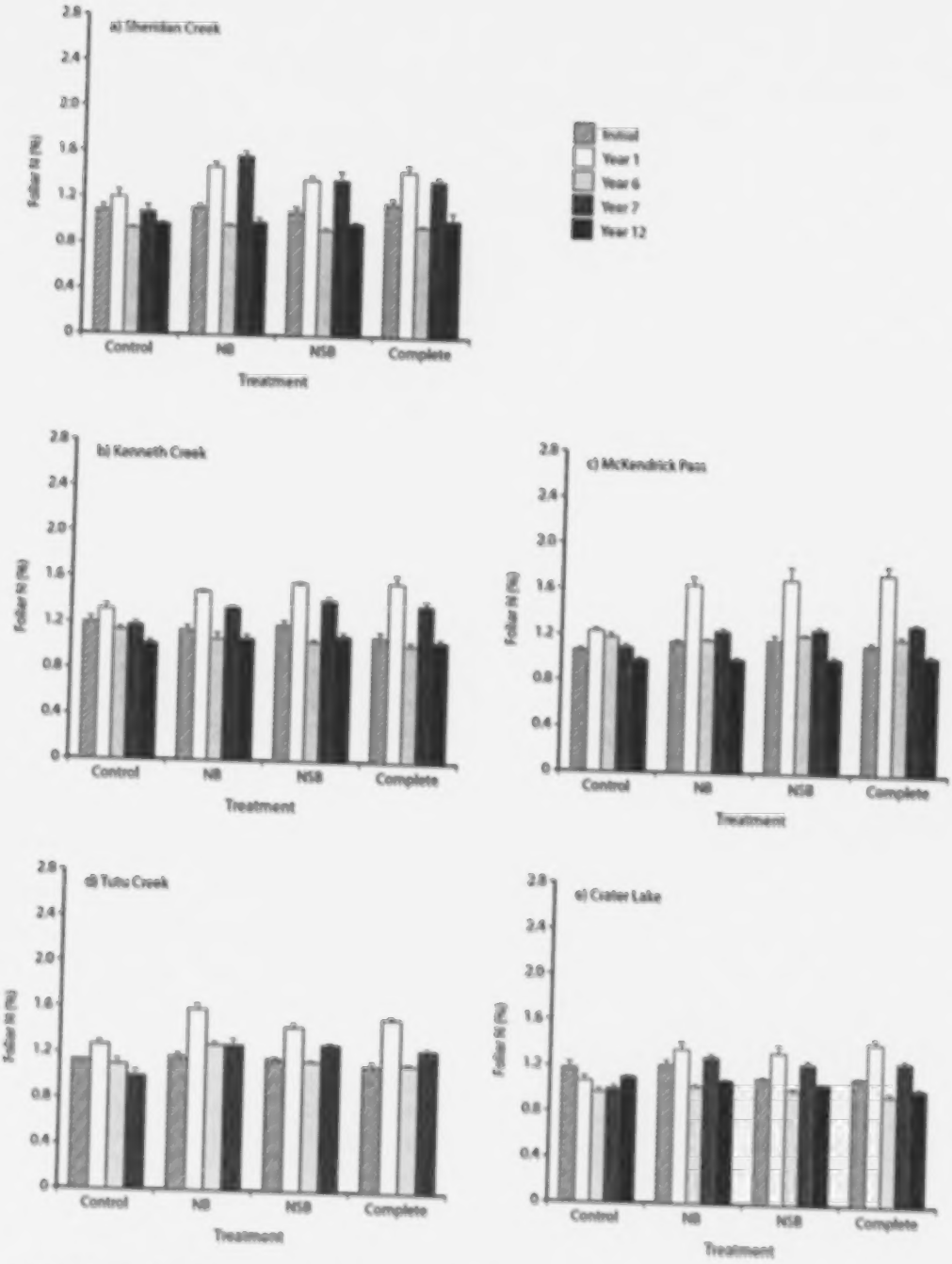

FIGURE 2 *Foliar nitrogen (N) concentration by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). Error bars represent standard error of the mean.*

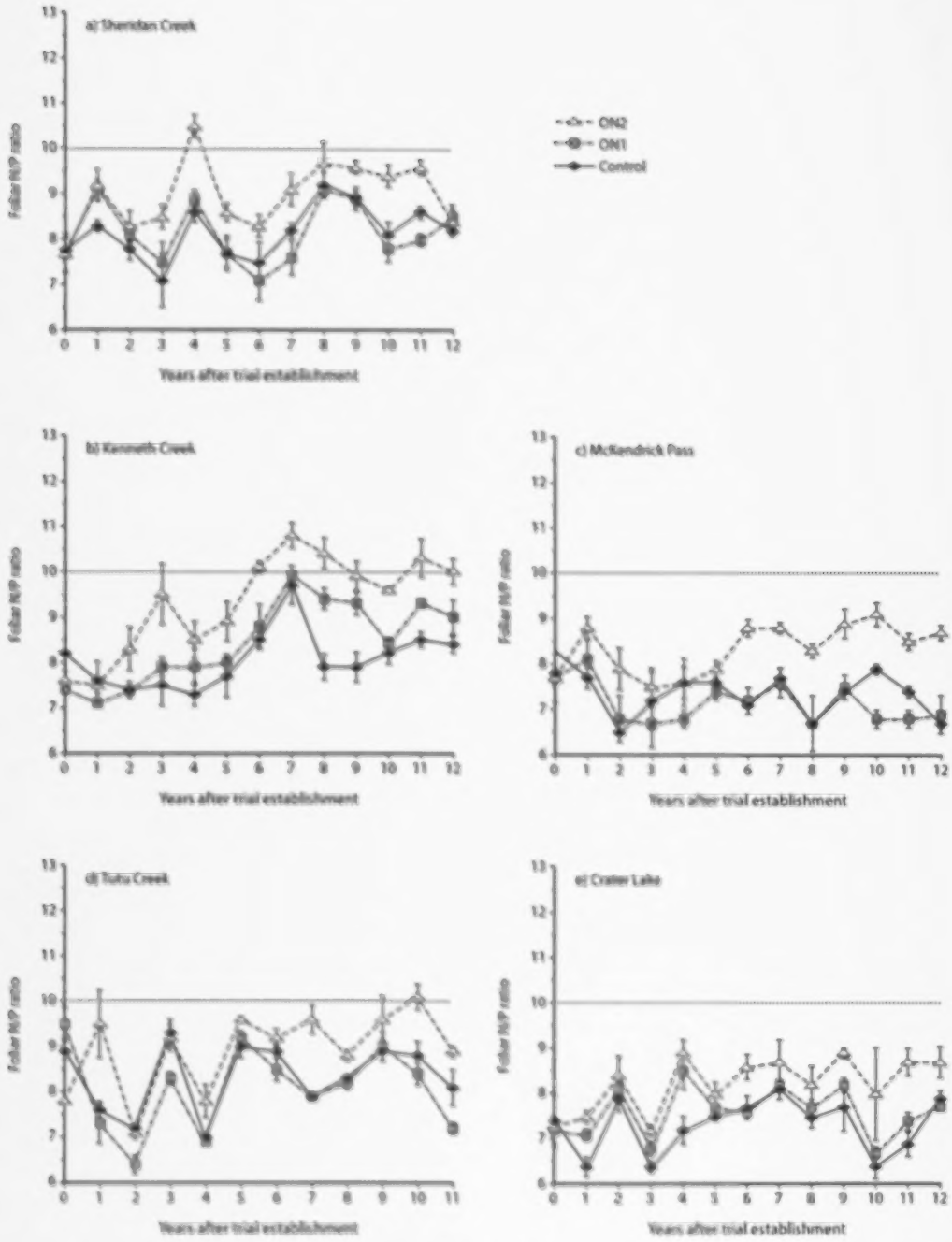

FIGURE 3 *Foliar nitrogen:phosphorus (N/P) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

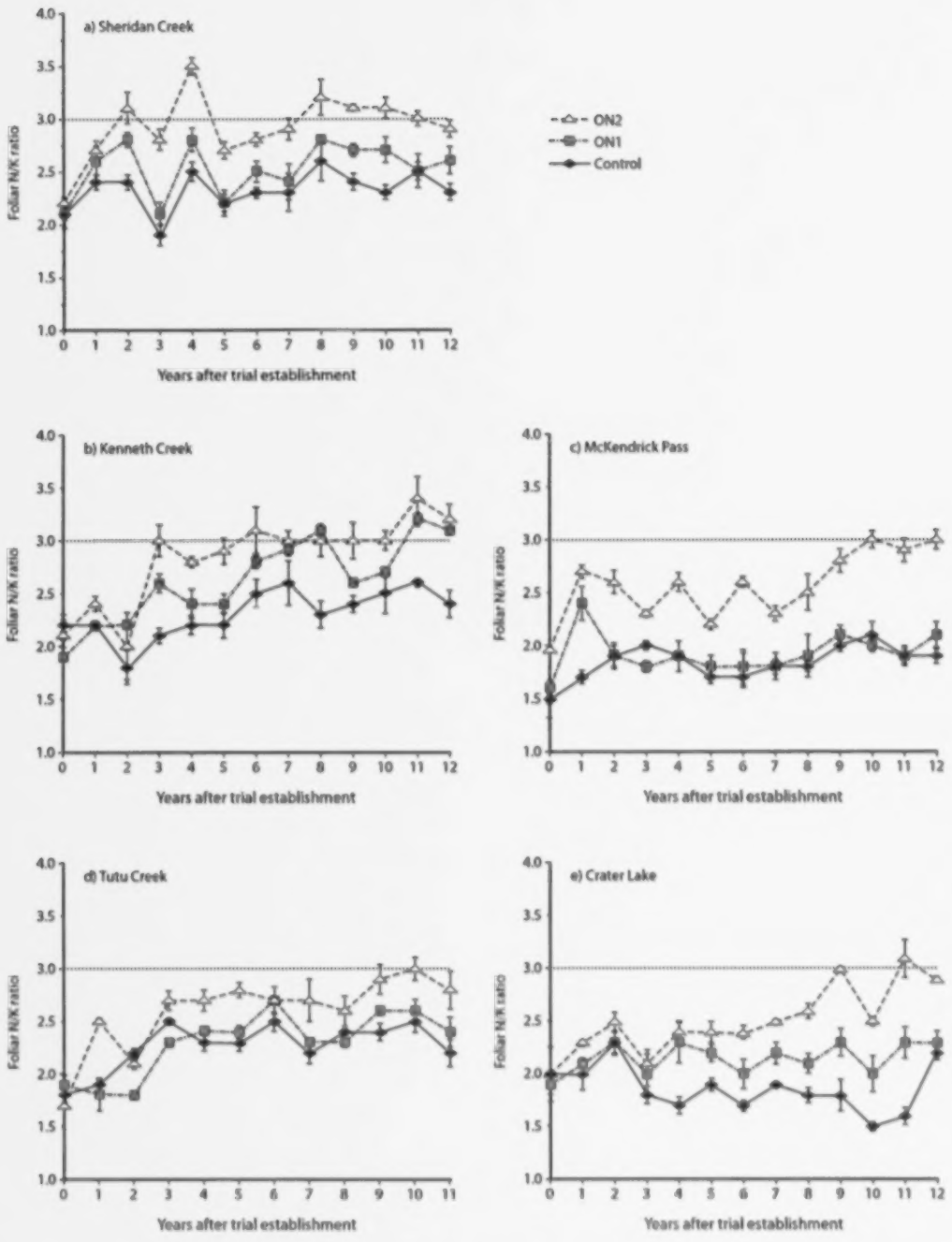

FIGURE 4 *Foliar nitrogen:potassium (N/K) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

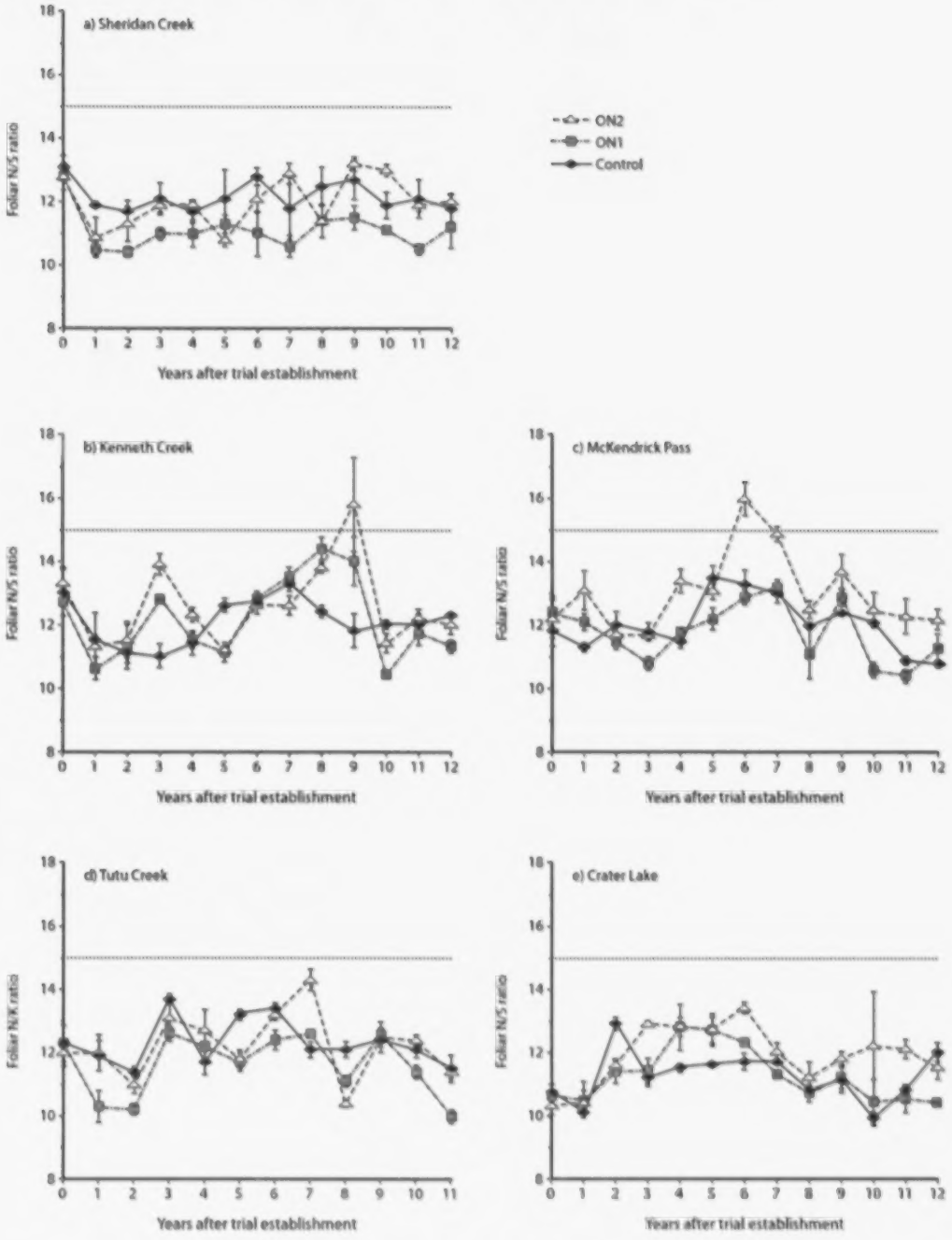

FIGURE 5 *Foliar nitrogen:sulphur (N/S) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

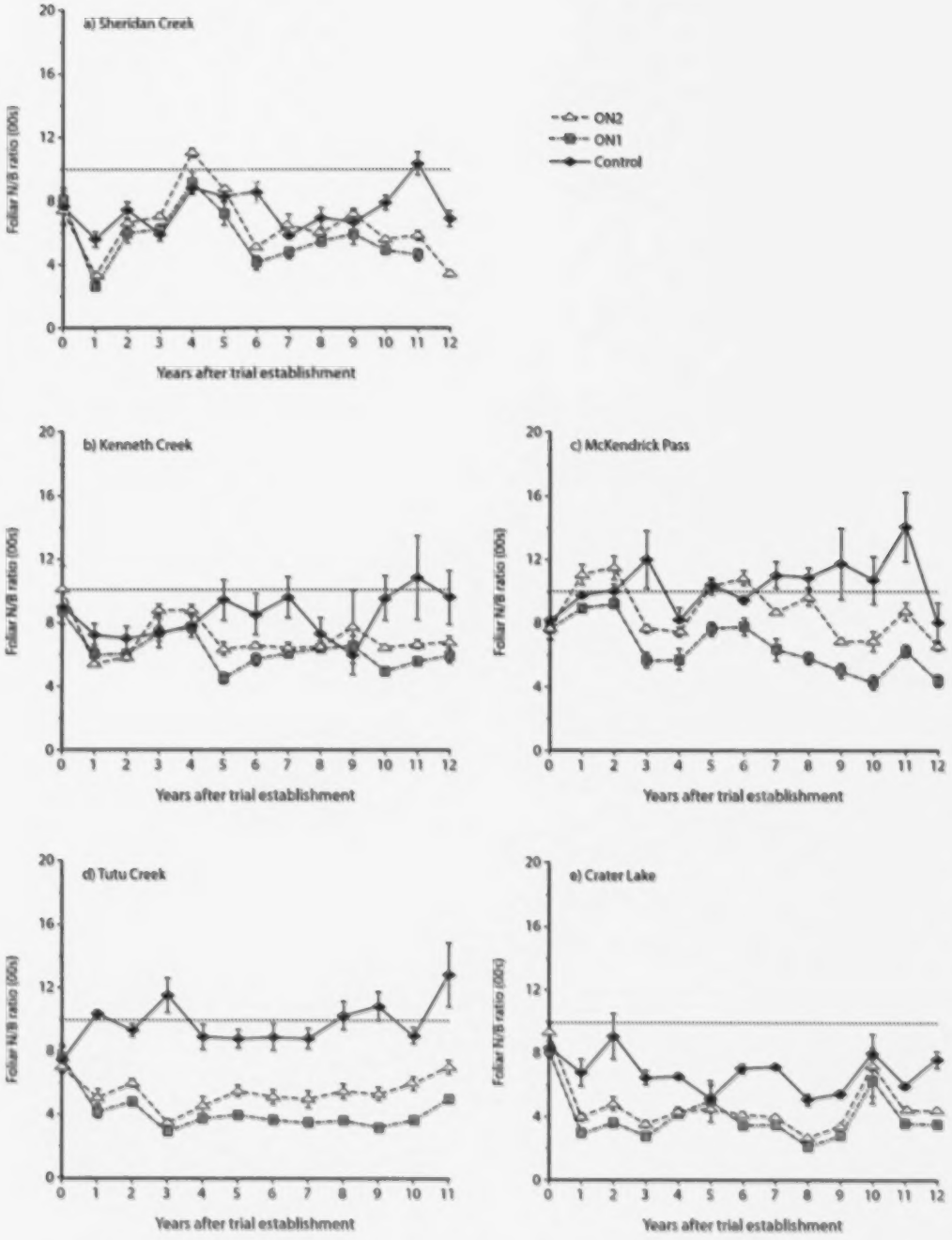

FIGURE 6 *Foliar nitrogen:boron (N/B) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

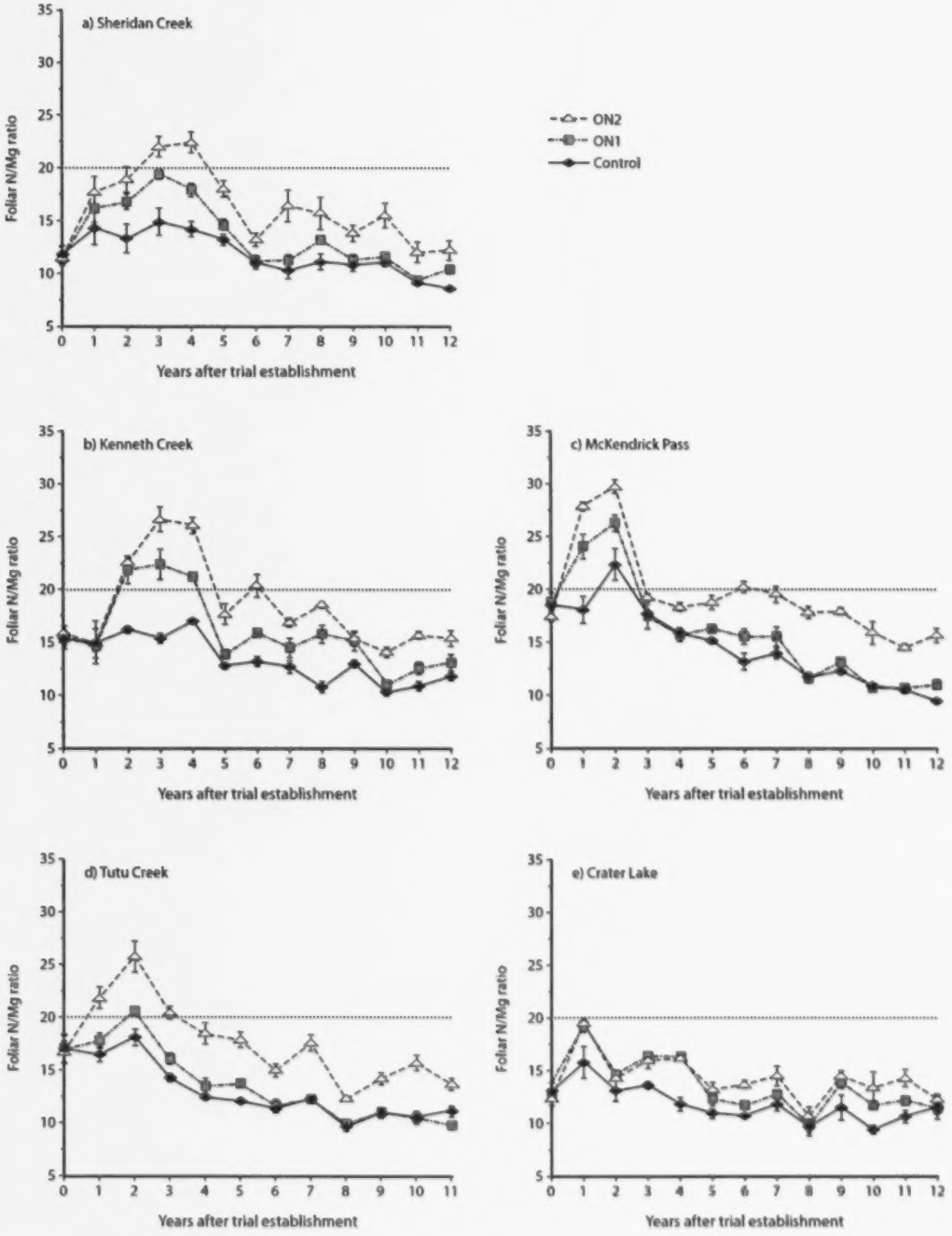

FIGURE 7 *Foliar nitrogen:magnesium (N/Mg) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

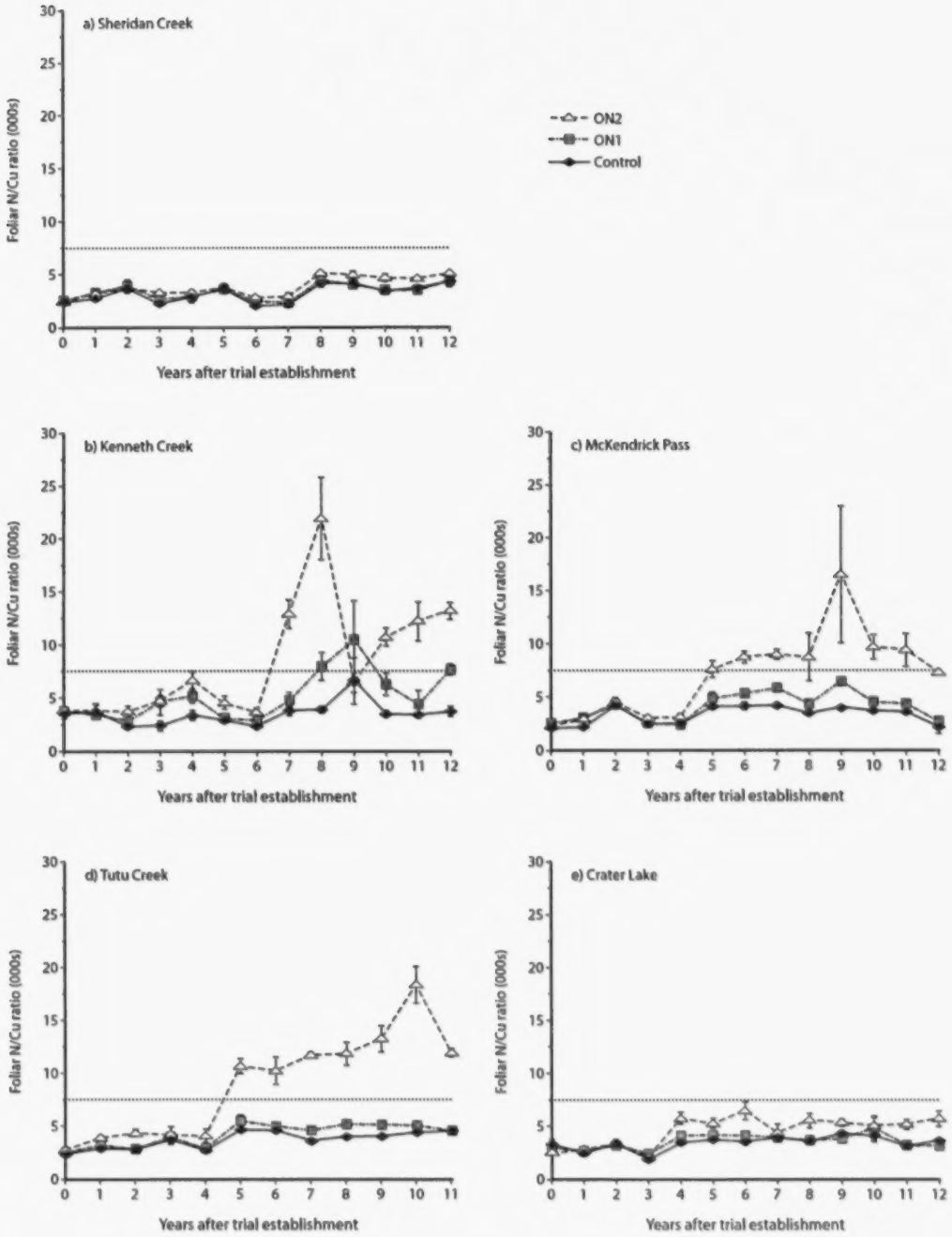

FIGURE 8 *Foliar nitrogen:copper (N/Cu) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

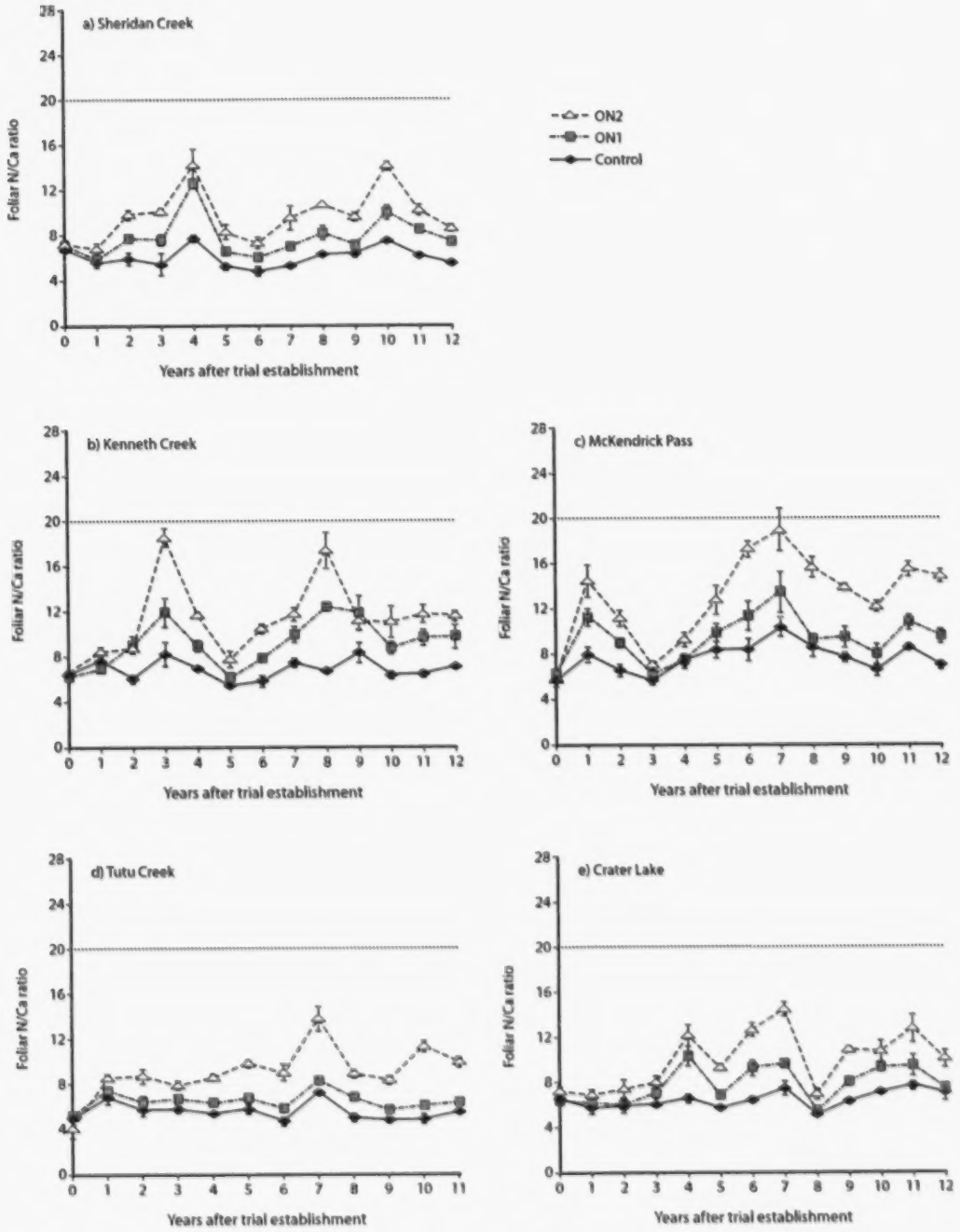

FIGURE 9 *Foliar nitrogen:calcium (N/Ca) ratio by treatment and year. For each installation, each plotted point represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

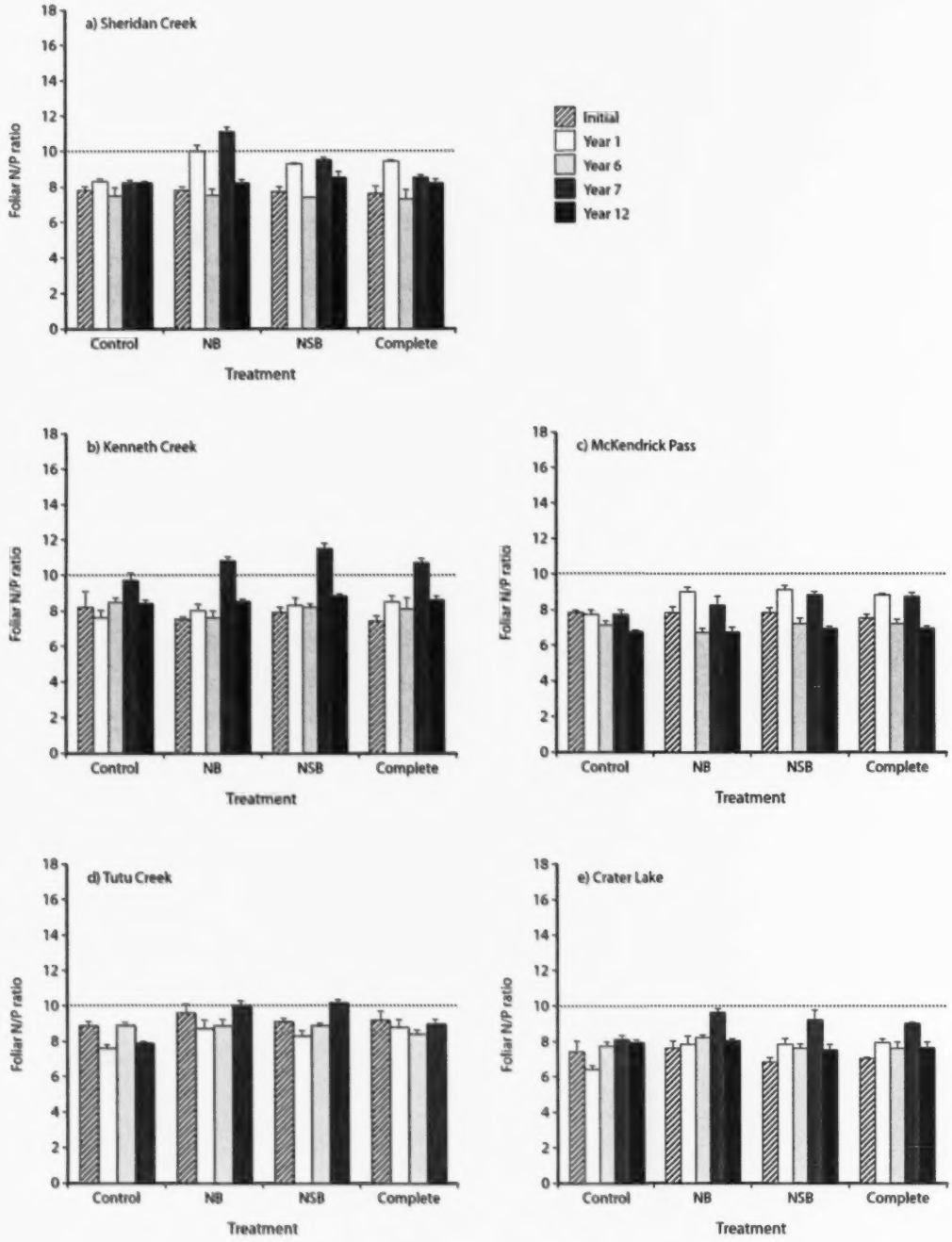

FIGURE 10 *Foliar nitrogen:phosphorus (N/P) ratio by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

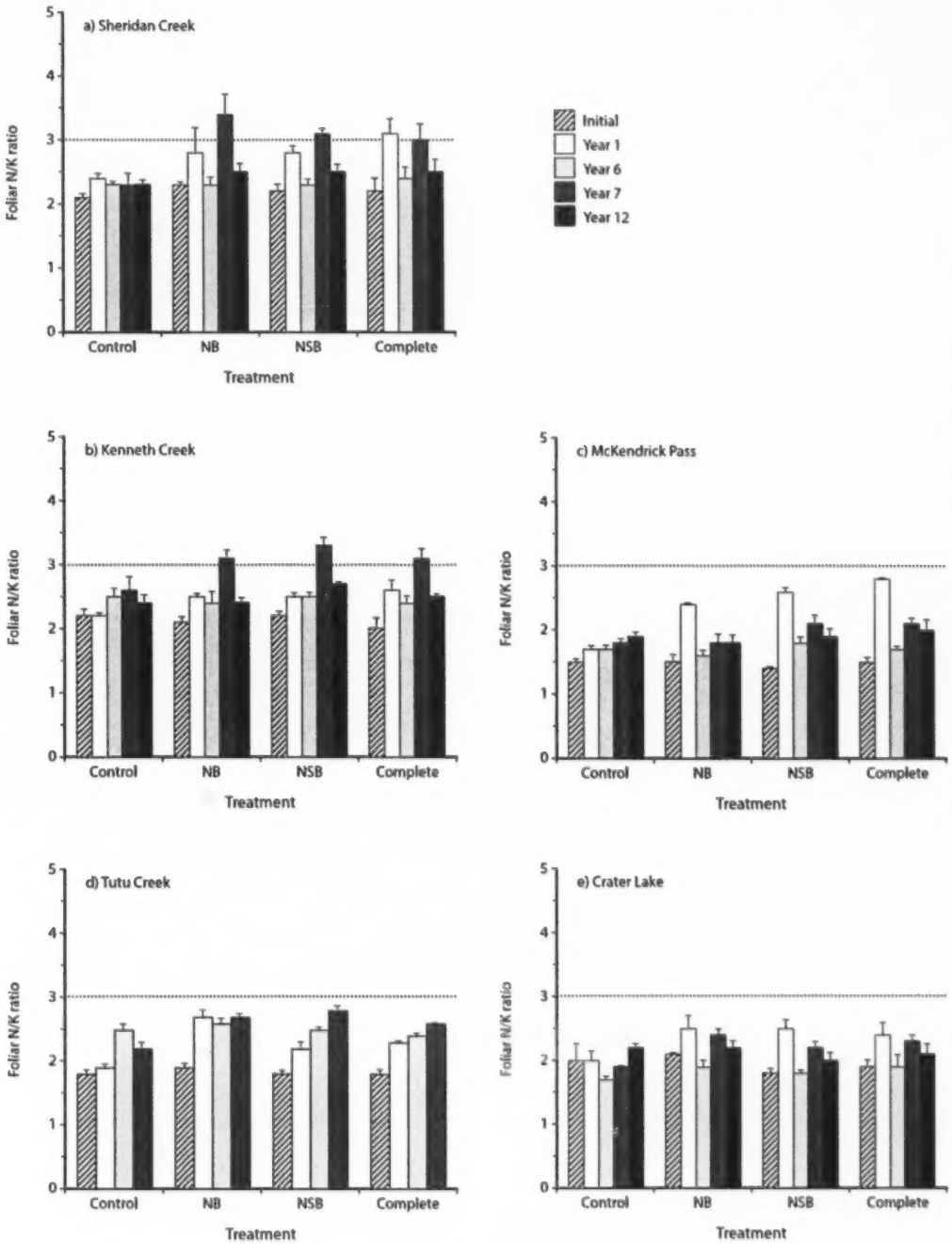

FIGURE 11 *Foliar nitrogen:potassium (N/K) ratio by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

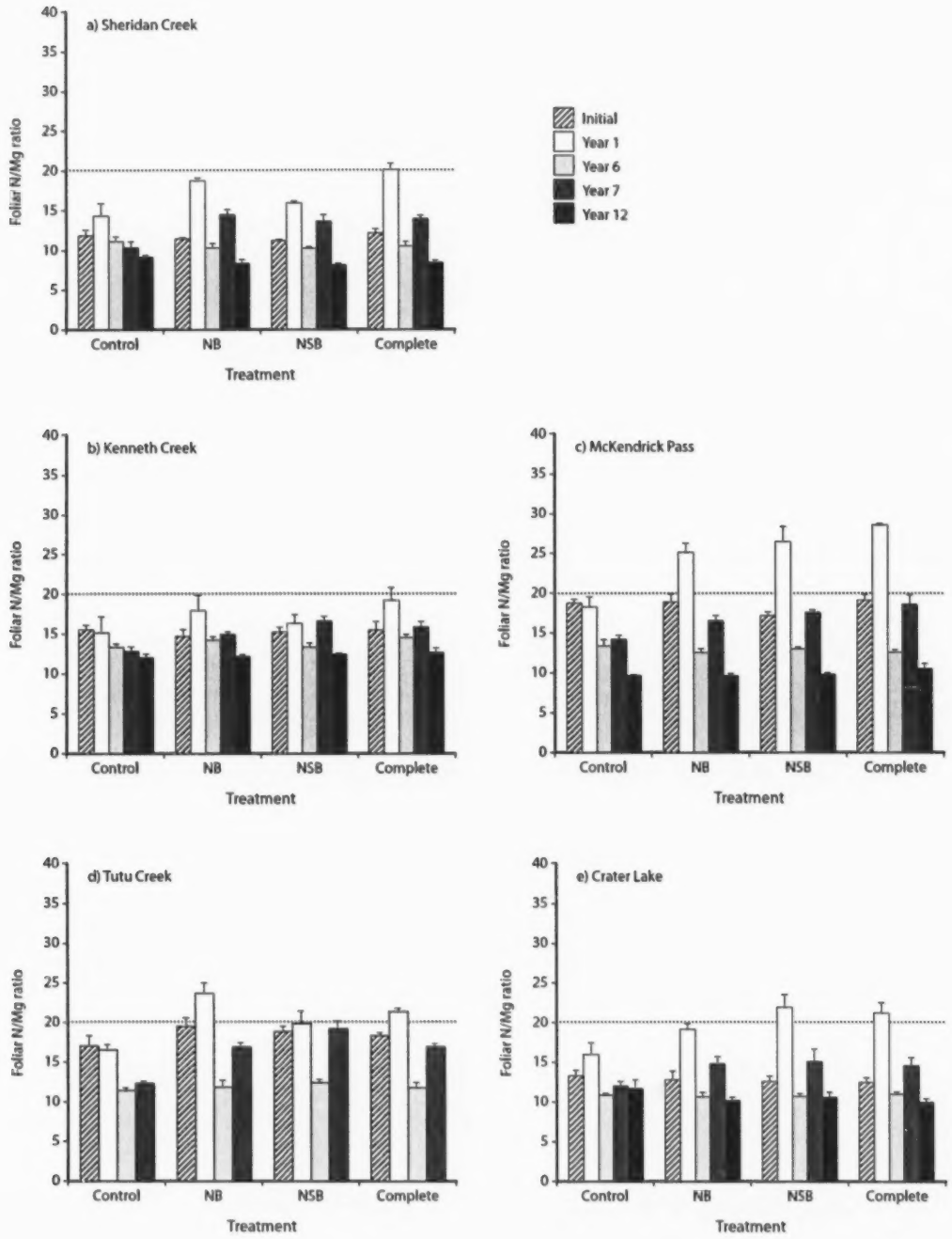

FIGURE 12 *Foliar nitrogen:magnesium (N/Mg) ratio by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

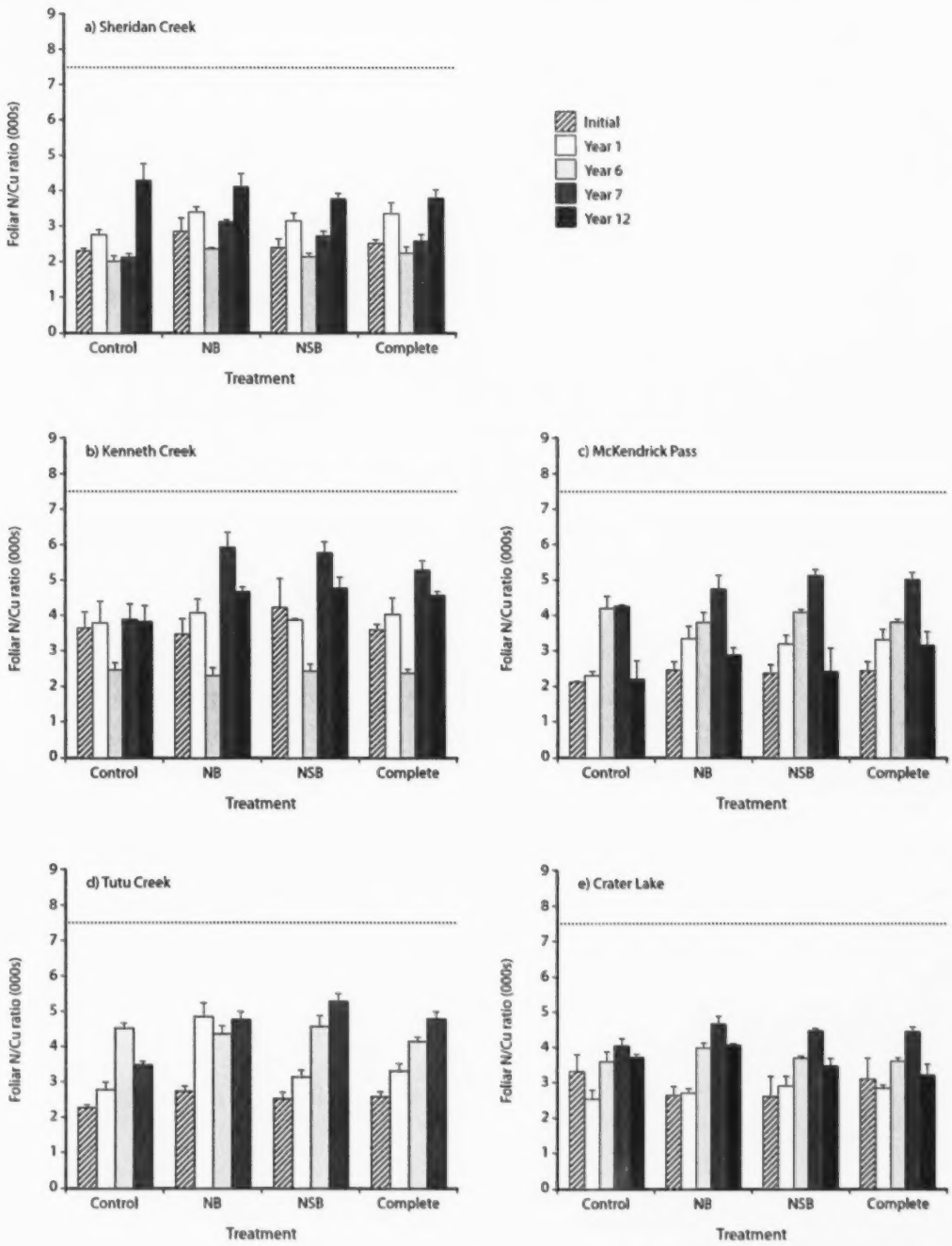

FIGURE 13 *Foliar nitrogen:copper (N/Cu) ratio by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

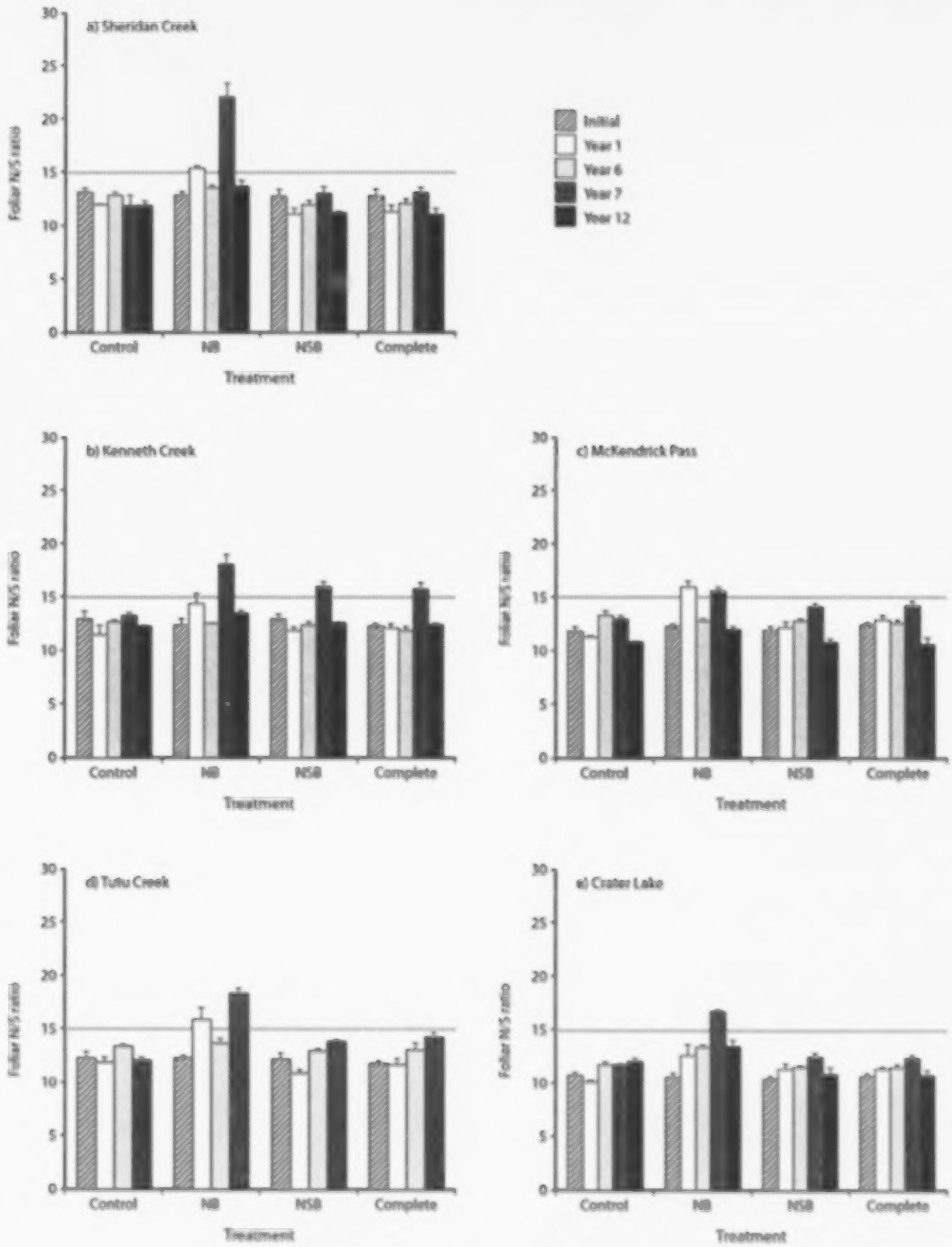

FIGURE 14 *Foliar nitrogen:sulphur (N/S) ratio by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

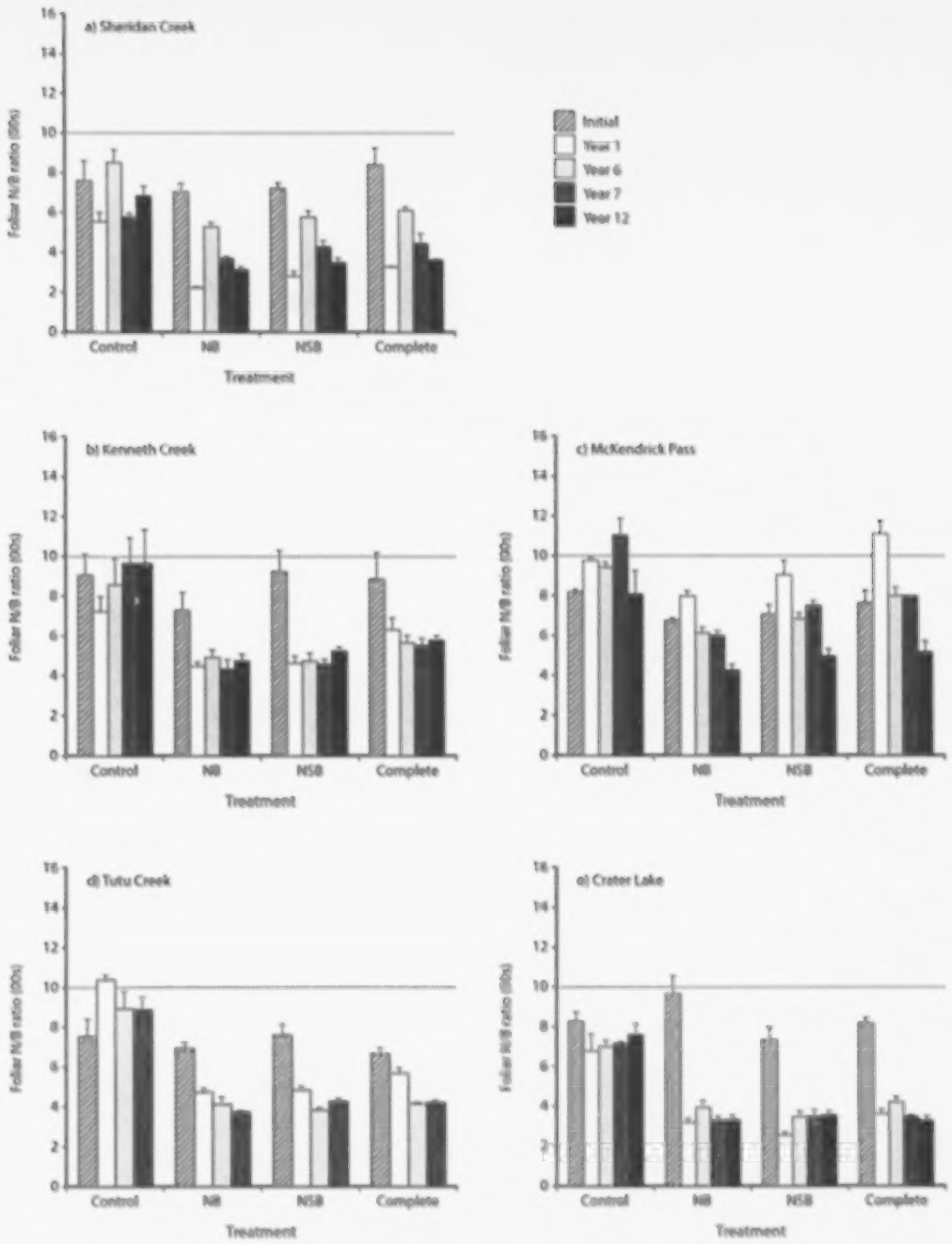

FIGURE 15 *Foliar nitrogen:boron (N/B) ratio by treatment and year. For each installation, each bar represents the mean of three composite samples (10 trees/composite). The dotted horizontal line represents the threshold value. Error bars represent standard error of the mean.*

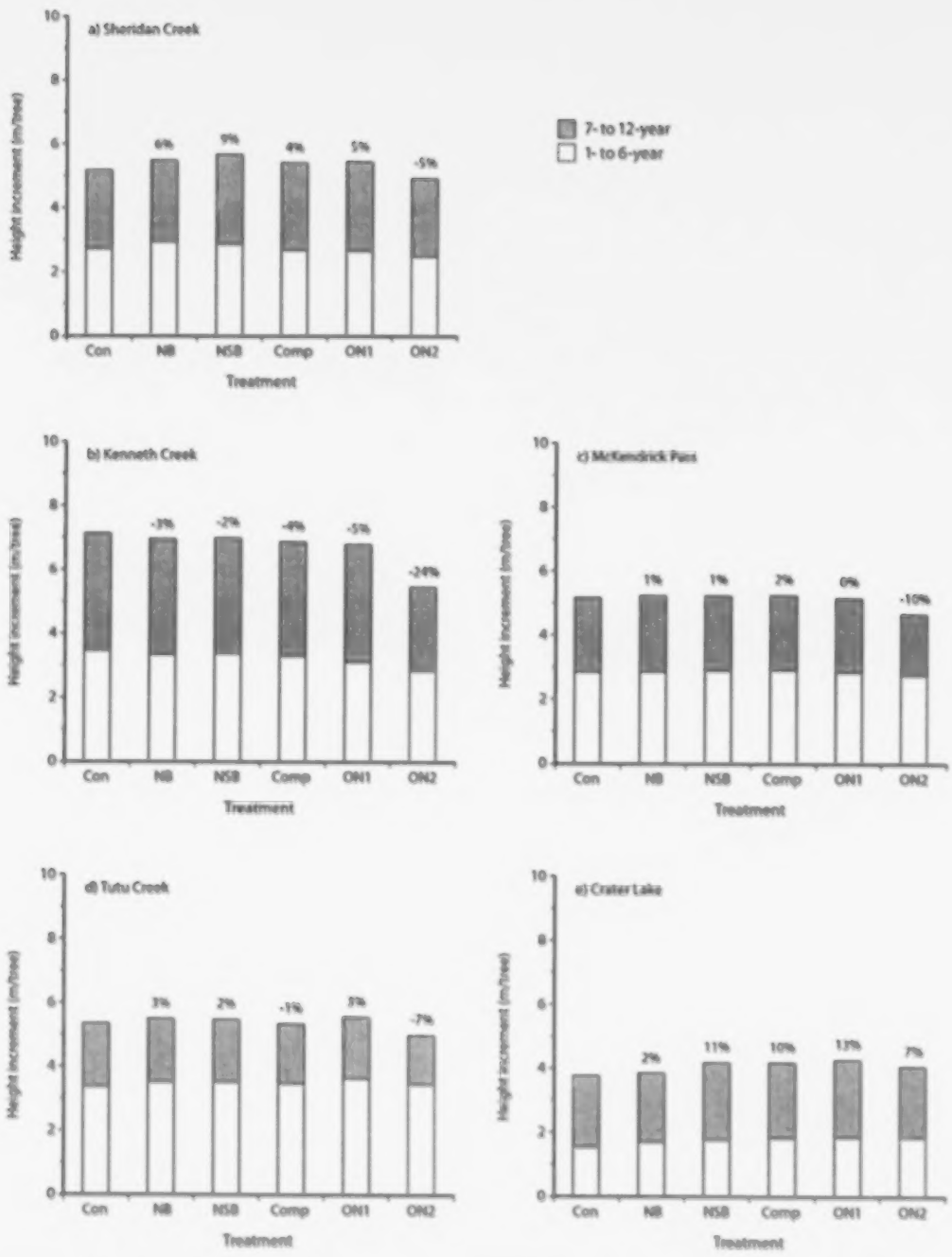

FIGURE 16 *Mean tree height increment by measurement period and treatment. Numbers above each bar indicate change relative to the control treatment over 12 years.*

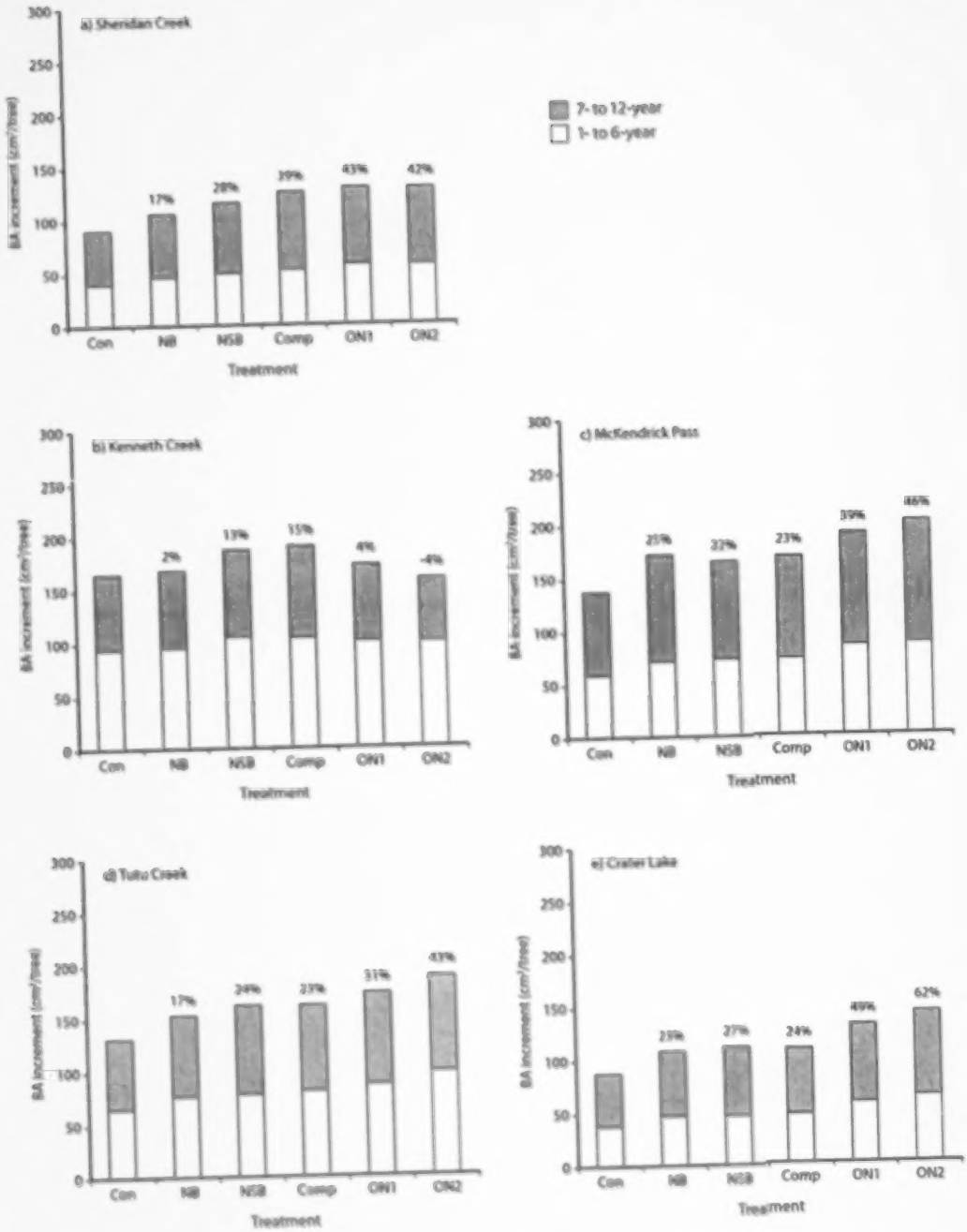

FIGURE 17 *Mean tree basal area increment by measurement period and treatment. Numbers above each bar indicate change relative to the control treatment over 12 years.*

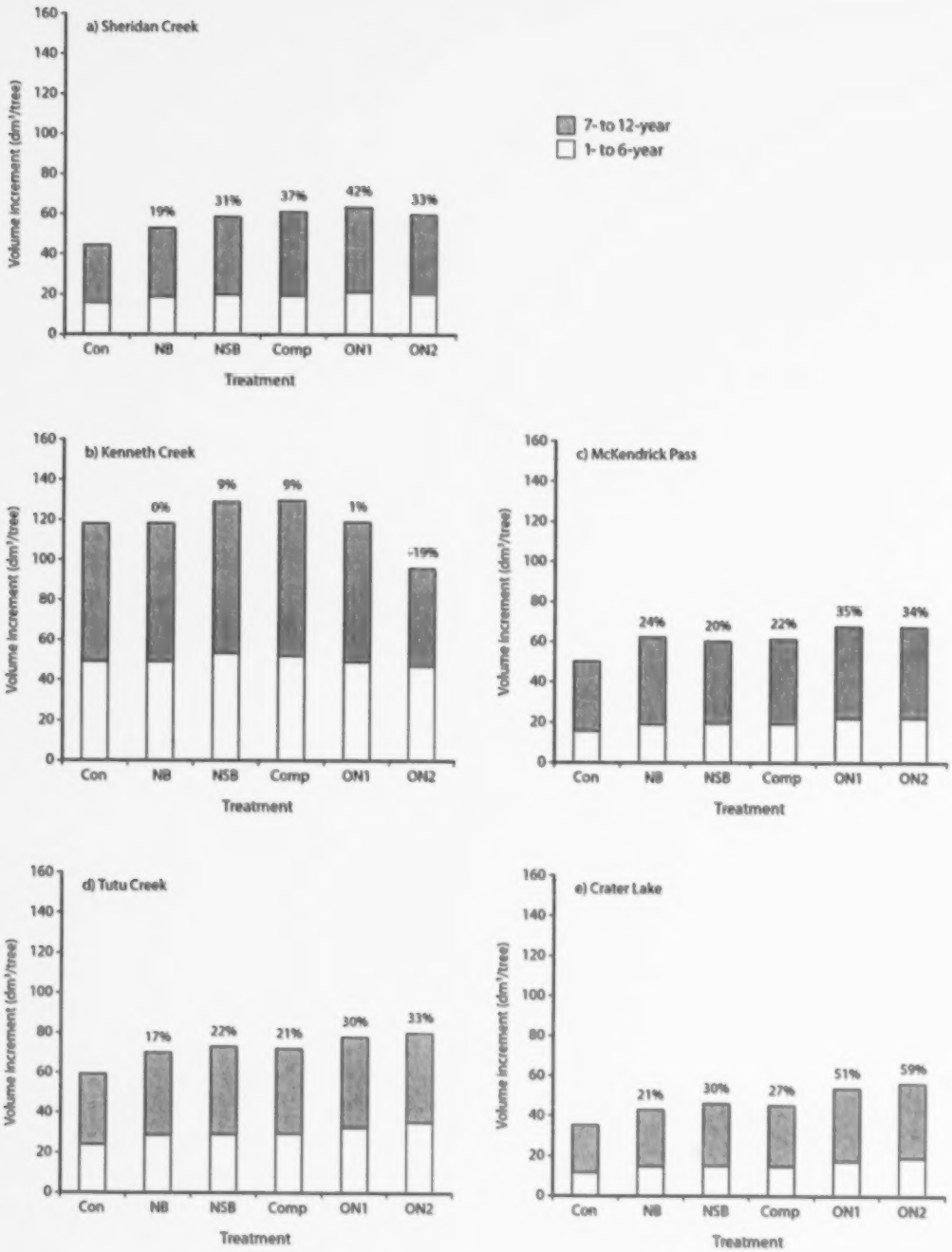

FIGURE 18 *Mean tree volume increment by measurement period and treatment. Numbers above each bar indicate change relative to the control treatment over 12 years.*

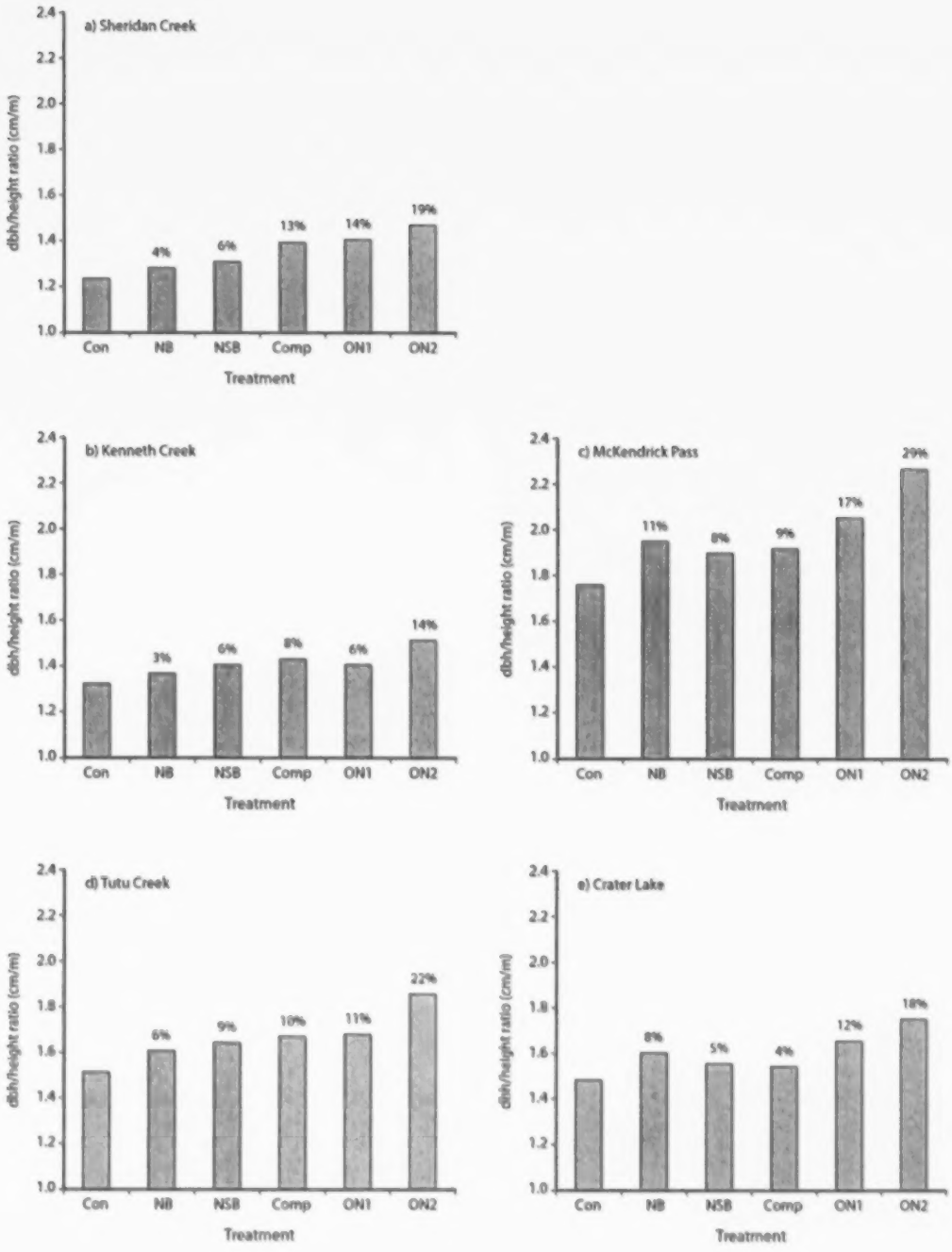

FIGURE 19 *Mean tree diameter at breast height (dbh)/height ratio at year 12 by treatment. Numbers above each bar indicate change relative to the control treatment over 12 years.*

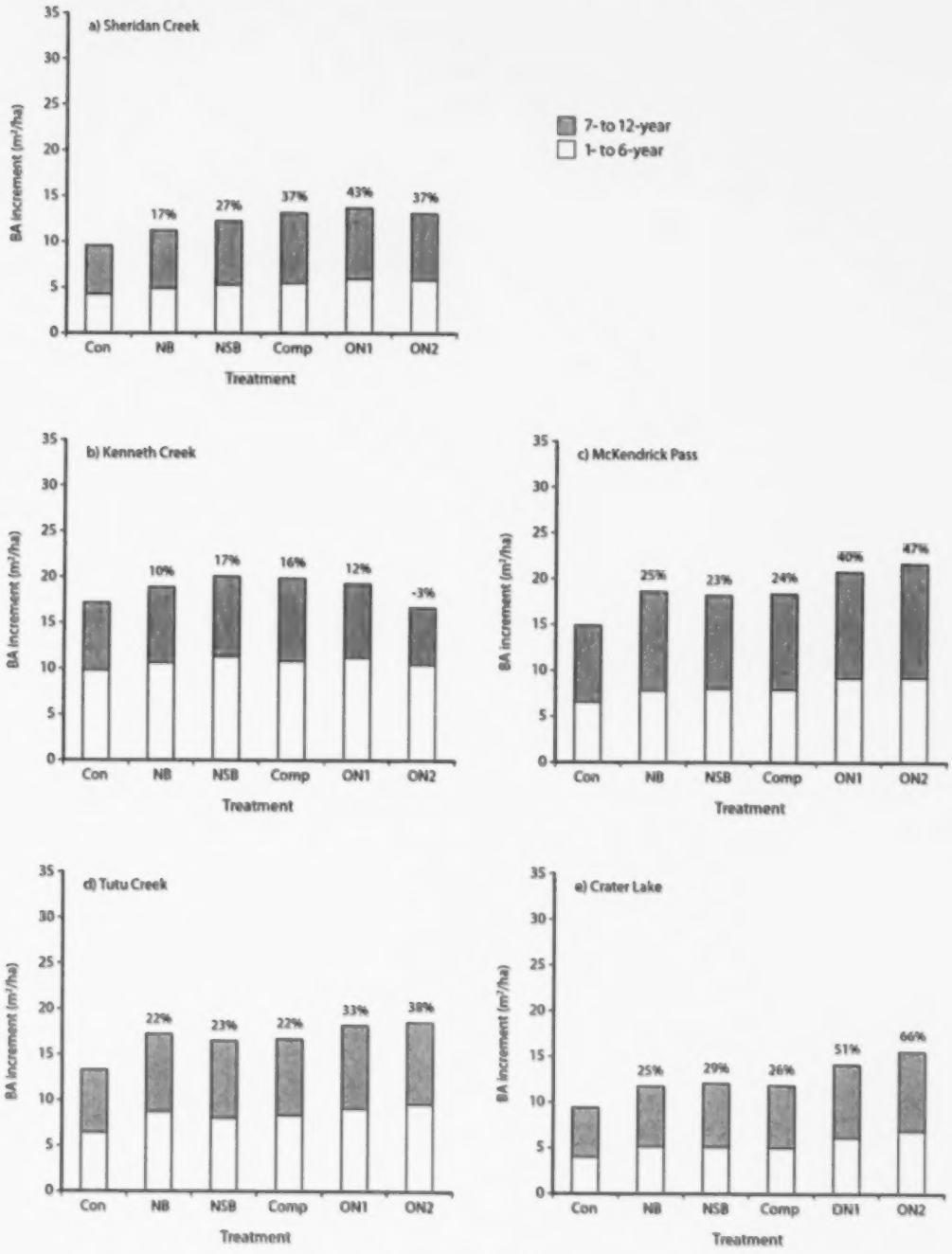

FIGURE 20 *Mean stand basal area increment by measurement period and treatment. Numbers above each bar indicate change relative to the control treatment over 12 years.*

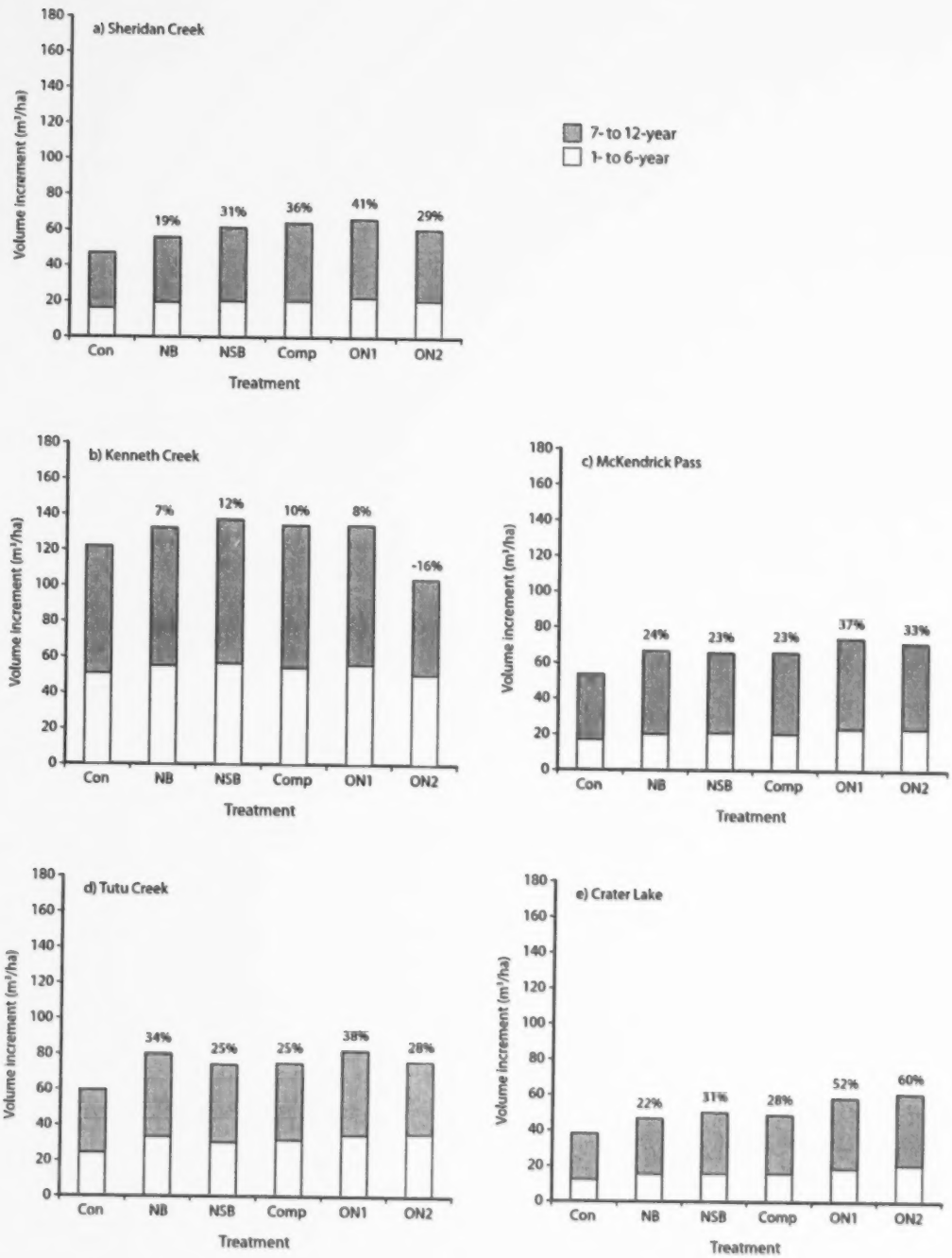

FIGURE 21 *Mean stand volume increment by measurement period and treatment. Numbers above each bar indicate change relative to the control treatment over 12 years.*

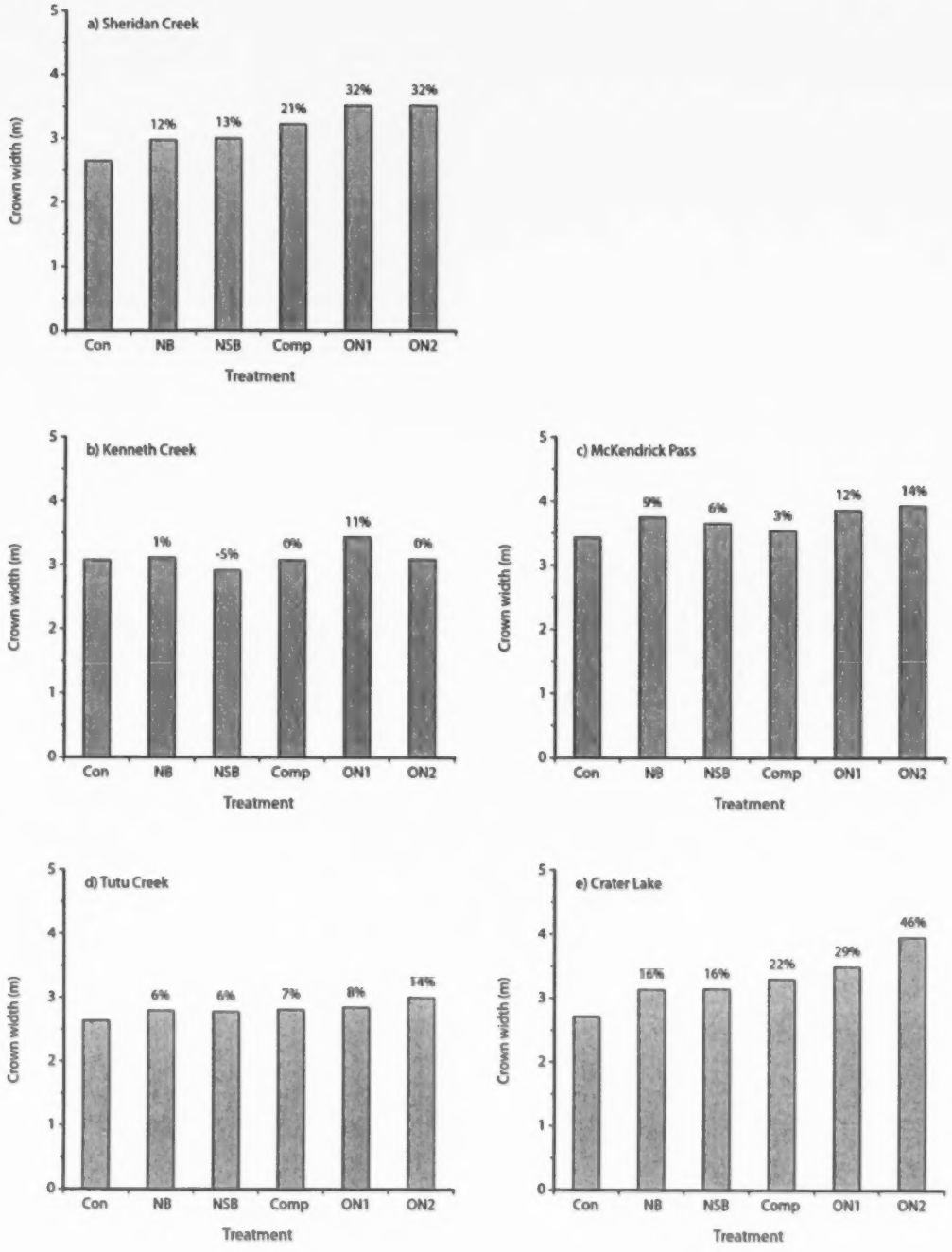

FIGURE 22 *Mean crown width at year 12 by treatment. Numbers above bars indicate change relative to the control treatment.*

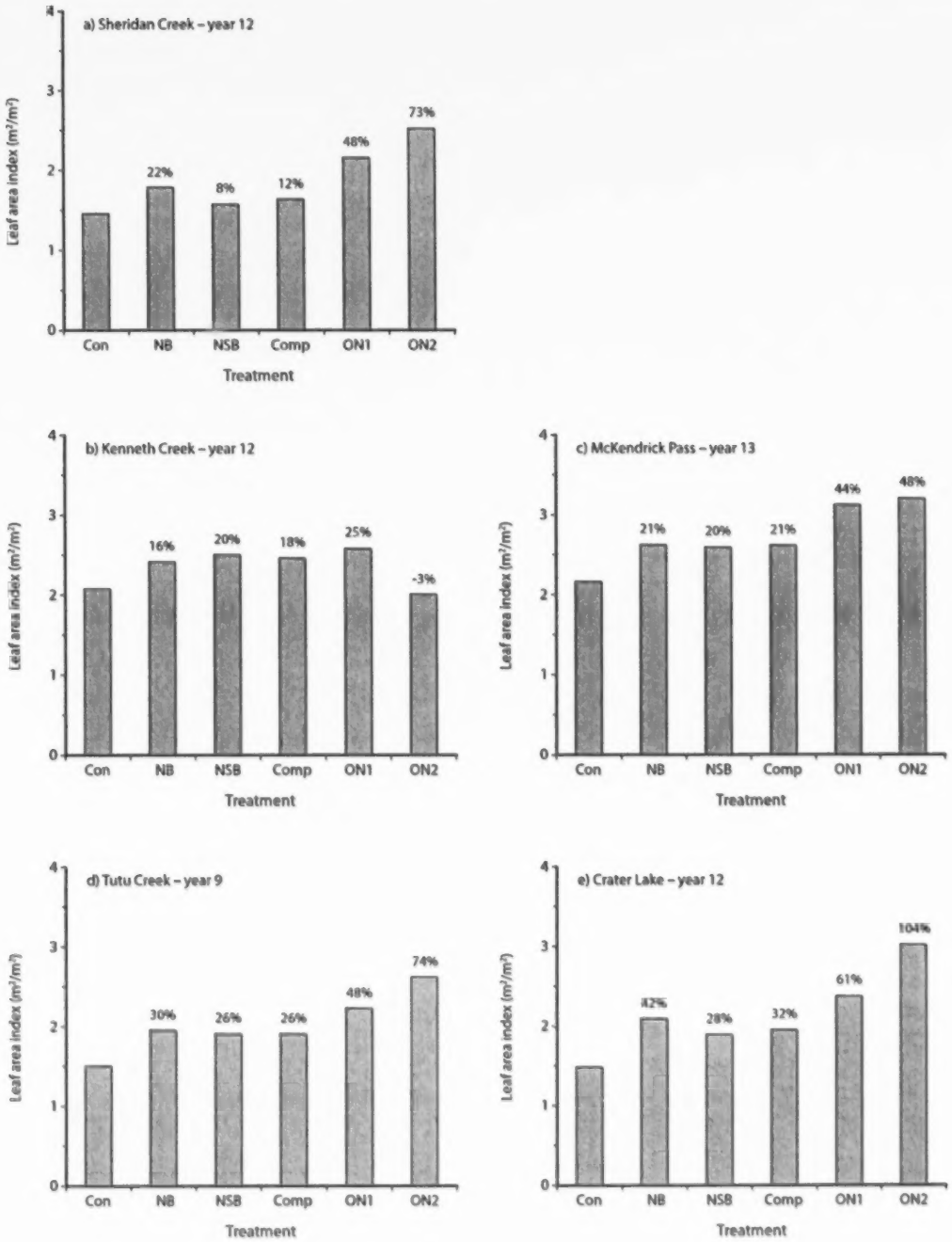

FIGURE 23 *Mean effective leaf area index by treatment. Measurements were obtained at year 9 (Tutu Creek), year 12 (Sheridan Creek, Kenneth Creek, Crater Lake), and year 13 (McKendrick Pass). Values above bars indicate change relative to unfertilized treatment.*

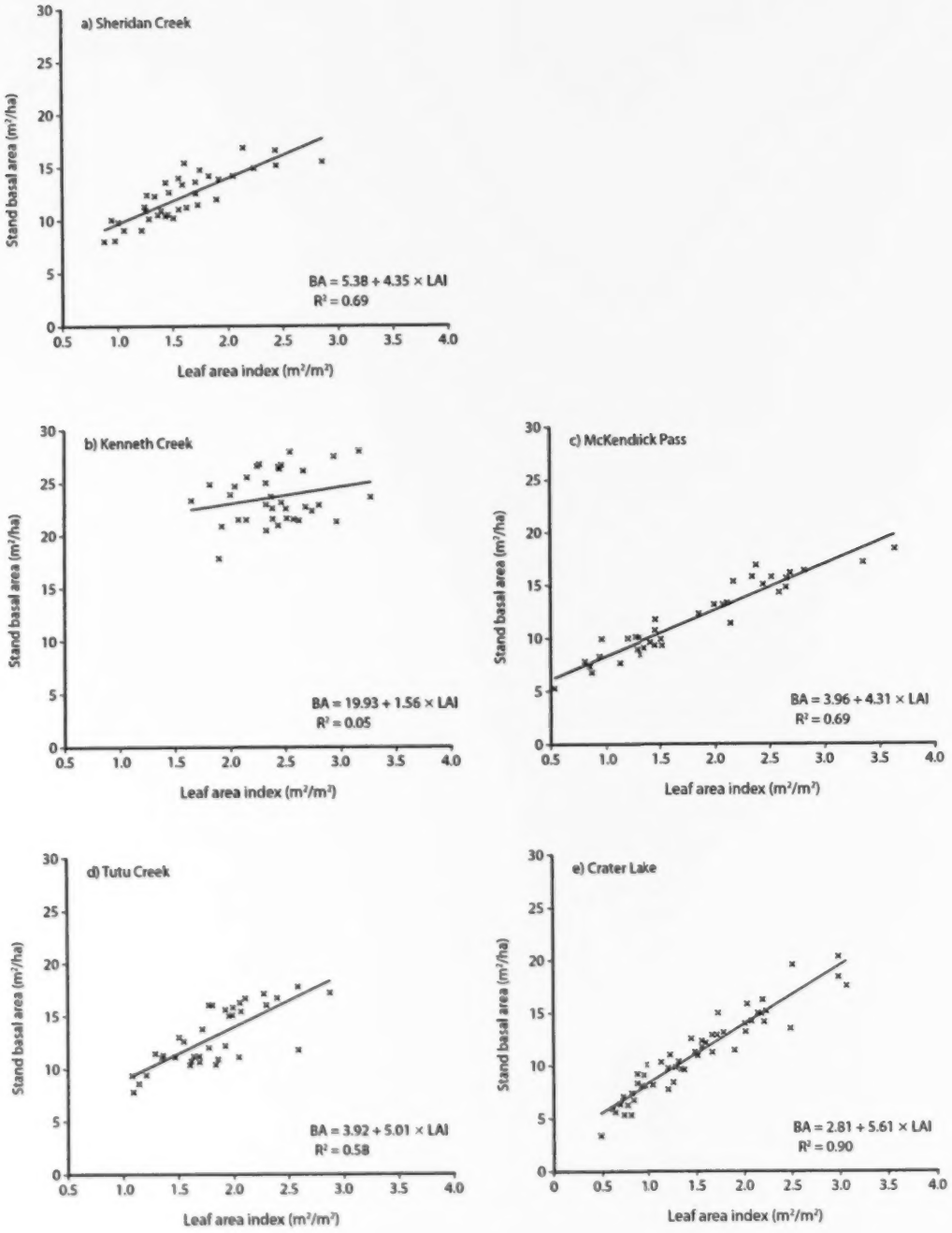
a) Sheridan Creek
Stand basal area (m²/ha)
Leaf area index (m²/m²)
BA = 5.38 + 4.35 × LAI
R² = 0.69
b) Kenneth Creek
BA = 19.93 + 1.56 × LAI
R² = 0.05
c) McKendrick Pass
BA = 3.96 + 4.31 × LAI
R² = 0.69
d) Tutu Creek
BA = 3.92 + 5.01 × LAI
R² = 0.58
e) Crater Lake
BA = 2.81 + 5.61 × LAI
R² = 0.90

FIGURE 24 *Relationship between stand basal area (m^2/ha) and leaf area index (m^2/m^2).*

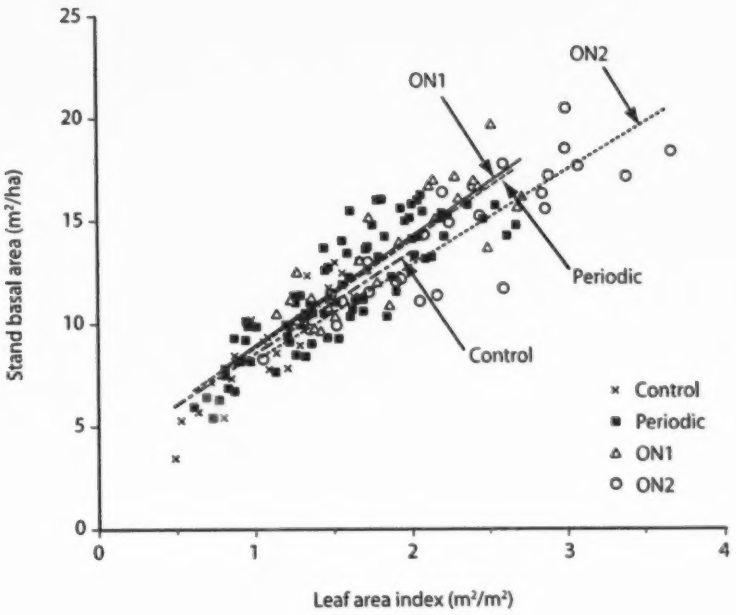

FIGURE 25 *Stand basal area (m^2/ha) per unit of leaf area index (m^2/m^2) for control, periodic (NB, NSB, complete), ON1, and ON2 treatments for all measurements and sites combined (Kenneth Creek excluded). Regression lines are shown for each treatment (as per Equation 3 in Table 5).*

After 12 years, four of five study sites showed statistically significant stand volume growth gains from two applications of NB, NSB, and complete fertilizers. However, even the largest relative stand volume response (36%) was considerably smaller than that reported following similar periodic fertilization of thinned lodgepole pine (1100 and 1600 sph) in central British Columbia (Brockley 2005). Also, the 12-year stand volume gains from two fertilizer applications (400 kg N/ha in total) in this study (8.5–17.2 m^3/ha) were within the range of previously reported lodgepole pine growth gains from a single fertilization with 200 kg N/ha (Brockley 1991, 1996, 2001a). The amount of N required to produce each extra unit of stand volume over 12 years (23–47 kg N/m^3) was larger than in most other lodgepole pine studies. The lower effectiveness and N conversion efficiency of periodic fertilization in this study may be partially explained by differences in stand origin and season of fertilizer application. In this study, all five stands were either planted or naturally regenerated following harvesting; these stand types are often less responsive to N fertilization than are fire-origin lodgepole pine (Brockley 1996). Although pre-fertilization foliar analysis suggests that all five sites were N deficient (Ballard and Carter 1986; Brockley 2001b), initial foliar N levels were higher than those usually observed in fire-origin stands (Brockley 1996). A negative relationship between lodgepole pine growth response to N fertilizer and pre-treatment foliar N concentration was reported by Brockley (2000). Also, fertilization in other studies was conducted in the fall when the typically cool and wet weather patterns help minimize N volatilization losses from applied urea (Nason and Myrold 1992). In this study, fertilizers were applied in the spring when warmer and drier conditions may have increased volatilization. Several additional factors likely contributed to the unresponsiveness of lodgepole pine to periodic fertilization at the Kenneth Creek study site. The sandy soils (with low cation exchange capacity), combined with moderate amounts of precipitation in the SBSwk subzone, may have contributed to leaching losses and poor uptake of applied nutrients. Also, foliage mass response in fertilized trees at Kenneth Creek was likely inhibited by the presence of *Dothistroma* needle blight (R. Reich, pers. comm.).

The significant incremental growth gains from added S and other nutrients at Sheridan Creek are consistent with results from other lodgepole pine studies that reported growth benefits by combining S and N in fertilizer prescriptions (Brockley 1996, 2000, 2004). Although not statistically significant, a trend of larger growth responses in NSB and complete treatments compared to the NB treatment was also evident at two other study sites. Whereas the foliar N/S ratio in the NB treatment at Sheridan Creek remained at or below the S deficiency threshold (~15) one year following initial fertilization, a foliar N/S ratio of 22 in the year following refertilization with NB indicated moderate to severe S deficiency (Ballard and Carter 1986; Brockley 2001b). The N/S ratio in NSB and complete treatments remained below the threshold value following refertilization. Similar foliar N/S trends occurred at Tutu Creek and Crater Lake. These results indicate that repeated N additions may exacerbate secondary nutrient deficiencies in some young lodgepole pine forests in central British Columbia unless S (and possibly other nutrients) is included with N in fertilizer prescriptions.

Although detailed bole measurements are required to accurately determine the effects of fertilization on stem shape, the proportionally greater 12-year radial growth than height growth at all study sites has apparently resulted in a more conical shape (i.e., larger dbh/height ratio) of fertilized trees, especially in the ON_2 treatment. A limited degree of crowding is required to maximize the height growth of lodgepole pine (Johnstone 1985). The relatively low density (i.e., 1100 sph) in these young lodgepole pine stands, and the opportunity for significant crown expansion, has likely exacerbated the conical shape of fertilized trees. Large stem taper may have undesirable effects on stand volume and lumber recovery at harvest (Middleton et al. 1995).

The 12-year relative stand volume gains in the ON_1 and ON_2 treatments (-16 to 60%) are generally within the range of growth responses reported for similar response periods in intensive fertilization studies with young Scots pine (*Pinus sylvestris* L.) and lodgepole pine forests (Mälkönen and Kukkola 1991; Tamm et al. 1999; Kishchuk et al. 2002). However, the growth responses are much smaller than those reported for repeatedly fertilized loblolly pine (*Pinus taeda* L.) and radiata pine (*Pinus radiata* D. Don) (Albaugh et al. 2004; Ringrose and Neilsen 2005). The growth responses are also much smaller than those measured in ON_1 and ON_2 treatments in interior spruce optimization experiments in central British Columbia.[2] Similarly, in Sweden, Norway spruce (*Picea abies* L.) has generally responded better than Scots pine to large and frequent nutrient additions (Tamm 1991; Tamm et al. 1999). Despite large increases in LAI relative to the control and periodic fertilizer treatments at four of the five study sites, yearly nutrient additions (ON_1 and ON_2) resulted in significantly greater 12-year volume increment than did periodic fertilization at only McKendrick Pass and Crater Lake. At Kenneth Creek, yearly fertilization resulted in significantly less stand volume increment than did periodic fertilization over 12 years. Similar negative dose-response relationships have been reported for heavily fertilized jack pine (*Pinus banksiana* Lamb) and Scots pine in boreal forests (Weetman et al. 1995; Tamm et al. 1999; Högberg et al. 2006). Several factors may have contributed to the relative ineffectiveness of large and frequent nutrient additions on lodgepole pine tree and stand growth in this study.

Although increased photosynthetic surface area usually has a positive effect on stem growth (Fagerström and Lohm 1977), larger amounts of C resources are required to support the increased crown mass. Also, increased production of foliage may result in reduced light intensity in the lower portion of the crown and decreased biomass production per unit of foliage (Brix 1981). Maier et al. (1998) reported large increases in stem and branch wood maintenance respiration rates following fertilization. Amponsah et al. (2004) reported preferential allocation of C to support growth of lower branches at Sheridan Creek. Similarly, increased growth allocation to branches was reported for Scots pine following long-term N fertilization (Mälkönen and Kukkola 1991). Unless associated with an increase in net photosynthesis, increased allocation to branches may reduce the stemwood response. Heavy branching may also reduce wood quality and value (Jozsa and Middleton 1994).

Disruptions in foliar nutrient balance caused by large and frequent N additions may have also contributed to the relatively poor BA and height growth of trees in the ON_2-fertilized treatment plots, especially at Kenneth Creek

2 R. Brockley, unpublished data, 2009.

where repeated fertilization did not stimulate crown development. For example, Cu deficiency symptoms (i.e., twisted stems and branches) were clearly evident in ON_2 treatment plots at Kenneth Creek, McKendrick Pass, and Tutu Creek. At these sites, foliar Cu levels (< 2–3 mg/kg) and N/Cu ratios (> 7500) were within the range associated with visual symptoms of Cu deficiency in radiata pine (Turvey 1984; Hopmans 1990). Foliar nutrient imbalance has been linked to poor growth and reduced growth efficiency (i.e., amount of stem growth per unit of leaf area) following intensive fertilization of Scots pine in Sweden (Tamm et al. 1999; Högberg et al. 2006) and of red pine (*Pinus resinosa* Ait.) in the northeastern United States (Bauer et al. 2004; Magill et al. 2004).

Overall, stand BA growth efficiency increased slightly (~ 5%) due to fertilization at the lodgepole pine study sites. Growth efficiency was higher in periodic and ON_1 treatments, but wood production per unit of leaf area apparently declined in ON_2-fertilized trees. Higher nitrogen levels in fertilized foliage typically improve growth efficiency by improving the rate of photosynthesis per unit of foliage area (Brix 1981). For example, photosynthetic efficiency of fertilized Norway spruce foliage was 10–20% higher than that of unfertilized foliage (Roberntz and Stockfors 1998; Bergh and Linder 1999). Similarly, Murphy et al. (1996) found 26% higher photosynthesis rates in fertilized than in unfertilized loblolly pine. Conversely, despite high foliar N levels, heavily fertilized red pine had significantly lower photosynthetic capacity than did control trees (Bauer et al. 2004). Free amino acids (mainly arginine) accumulated in the foliage of heavily fertilized trees, thereby diverting N away from photosynthesis and reducing C assimilation. In radiata pine, foliar nutrient imbalances following large N additions also resulted in highly increased arginine levels in foliage (Lambert 1986). Interestingly, Lambert (1986) reported a strong positive correlation between foliar arginine concentration and tree infection level of *Dothistroma* needle blight. At Kenneth Creek, the observed symptoms of *Dothistroma* infection were particularly severe in the ON_2-fertilized treatment (R. Reich, pers. comm.).

Several factors likely contributed to the development of foliar nutrient imbalances in ON_2-fertilized trees at Kenneth Creek and, to a lesser degree, at other study sites. Low foliar Cu levels and high N/Cu ratios at Kenneth Creek may be related to the coarse-textured soils derived from glaciofluvial outwash. Other studies indicate that Cu deficiency may occur on acidic, sandy soils (Will 1985; Turvey and Grant 1990). Several studies have documented decreases in mineral soil pH following repeated fertilization, with the greatest declines associated with high N application rates (Nilsson et al. 1988; Tamm and Popovic 1995; Fox 2004; Brockley and Sanborn 2009). Increased soil acidity is often associated with higher solubility of aluminum ions in soils, which may, in turn, interfere with the uptake of Cu, Ca, and other nutrients (Ryan et al. 1986; Sverdrup et al.1992; Cronan and Grigal 1995). Also, the high soil nitrate (NO_3) and sulphate (SO_4) levels measured after 12 years of repeated fertilization at Kenneth Creek (Brockley and Sanborn 2009) may have facilitated leaching losses of N, S, and base cations. Although leaching losses were not quantified, the larger amount of soil N in the forest floor and upper mineral soil (0-20 cm) in ON_1 and ON_2 treatment plots relative to control plots at Kenneth Creek was equivalent to only 19% and 24%, respectively, of the total amount of fertilizer N applied over 12 years (Brockley and Sanborn 2009). This is lower than the mean percent soil N recoveries (~40%) reported

from a wide variety of repeatedly fertilized forests (Johnson 1992; Homann et al. 2001). Similarly, only 17–19% of the added S was accounted for in soils at Kenneth Creek after 12 years (Brockley and Sanborn 2009). Leaching losses in N-saturated soils have been implicated as a cause of forest decline in Europe (van Dijk and Roelofs 1988; Huttl 1990). Finally, fertilizer-induced changes in soil biota and fine roots may have influenced nutrient availability and uptake. Berch et al. (2006) reported a significant depression of the components of the mesofauna and microbial communities in the ON_2 treatment at the Sheridan Creek study site. Yearly fertilization also reduced fine root activity, fine root length, and ectomycorrhizal colonization and community structure (Berch et al. 2006). These below-ground changes may have contributed to foliar nutrient imbalance in the ON_2 treatment at Sheridan Creek (and possibly other sites) by reducing soil nutrient availability and uptake. Reduced fine root activity, fine root length, and ectomycorrhizal development may have also increased the susceptibility of repeatedly fertilized trees to moisture stress under droughty soil conditions. Decreased root mass and reduced mycorrhizal infection is a basic characteristic of declining conifer forests in both Europe and the United States (Aber et al. 1989).

5 SUMMARY AND MANAGEMENT IMPLICATIONS

When applied at 6-year intervals to 9- to 15-year-old lodgepole pine stands, two applications of urea (totalling 400 kg N/ha), with and without other added nutrients, produced 12-year stand volume increments that were 7–36% higher than control values. In absolute terms, stand volume gains ranged from 8.5 to 17.2 m^3/ha over 12 years. These results are within the range of previously reported effects of a single fertilization (200 kg N/ha) on the growth of young lodgepole pine. The amount of N required to produce each extra unit of stand volume over 12 years (23–47 kg N/m^3) was larger than in most other lodgepole pine studies. The relatively low effectiveness and N conversion efficiency of periodic fertilization in this study may be partially explained by differences in stand origin and season of fertilization. All five stands were either planted or naturally regenerated following harvesting; these stand types are often less N deficient than are fire-origin lodgepole pine. Also, urea fertilizers are usually applied in the fall when the typically cool and wet weather patterns help minimize N volatilization losses. All fertilizers in this study were applied in the spring when warmer and drier conditions may increase volatilization, thereby potentially decreasing the effectiveness of fertilization.

Incremental benefits of combining S (and other nutrients) with N were clearly evident at only one study site after 12 years. However, an overall trend of larger growth responses in NSB and complete treatments compared to the NB treatment indicates that repeated N additions may exacerbate secondary nutrient deficiencies in some young lodgepole pine forests in central British Columbia unless S (and possibly other nutrients) is included with N in fertilizer prescriptions.

The effects of continued periodic fertilization on future stand development and yield can be predicted by manually applying estimated fertilization growth response to the modelled growth of an unfertilized stand in the Table Interpolation Program for Stand Yield information (TIPSY) (Mitchell et al.

2007). For example, TIPSY suggests that a merchantable volume of 250 m^3/ha for an unfertilized lodgepole pine plantation (site index = 21 m at 50 years; 1100 sph) would be attained at a stand age of about 45 years. Assuming each fertilizer application increases 6-year stand volume increment by 25% relative to an unfertilized stand, repeated fertilization (at 15, 21, 27, and 33 years) would reduce the time required to achieve a similar merchantable volume by about 6 years (stand age of 39 years). Viewed another way, TIPSY indicates that a 15-year-old unfertilized stand would produce a harvest of 206 m^3/ha of merchantable volume in another 25 years (i.e., stand age 40). If fertilized at 15, 21, 27, and 33 years, the same 40-year-old stand would produce a merchantable harvest of about 256 m^3/ha. Therefore, by reducing rotation length or increasing yield, periodic fertilization of young, nutrient-deficient lodgepole pine would likely help mitigate future timber supply shortfalls in the British Columbia Interior. The high costs of repeated fertilization (and increased cost per m^3 of harvested volume) would be partially offset by the extra 10.8 Mg/ha of stemwood C sequestered over 25 years.[3] Substantial amounts of C may also be sequestered in soils and forest floors of repeatedly fertilized forests (Hyvönen et al. 2008). The incremental increases in above- and belowground net C stocks in repeatedly fertilized forests may provide marketable greenhouse gas offsets in an emerging global C economy.

Yearly applications of N and other nutrients produced variable results, with 12-year stand volume increments ranging from 16% lower (-19.5 m^3/ha) to 60% higher (22.8 m^3/ha) than control values. Excluding Kenneth Creek (where growth in the ON_2 treatment was less than in the control), the amount of N required to produce each extra unit of stand volume over 12 years was generally larger in the ON_1 (range 36–42 kg N/m^3) and ON_2 (range 59–113 kg N/m^3) treatments than in periodic treatments. Poor growth response in some ON_2-fertilized treatment plots was typically associated with foliar nutrient imbalances (e.g., N/Cu, N/Mg) and lower growth efficiency (i.e., wood production per unit of leaf area). Overall, the 12-year results indicate that large and frequent nutrient additions are relatively ineffective and inefficient in stimulating the growth of young lodgepole pine. Similar results have been reported for intensively fertilized jack pine and Scots pine. There are too few long-term studies that have tested different fertilization regimes over a broad range of climatic and site productivity conditions to make reliable species generalizations. However, the much larger growth responses and superior N conversion efficiencies that have been reported for repeatedly fertilized loblolly pine and radiata pine indicate that *Pinus* species growing in temperate and sub-tropical climates may be better suited to the N-rich regimes created by intensive fertilization than are *Pinus* species growing in sub-boreal and boreal forests. The lodgepole pine and Scots pine results also contrast sharply with the large growth gains achieved in the small number of sub-boreal and boreal Norway spruce and interior spruce nutrient optimization studies in Sweden and British Columbia. These preliminary results indicate that *Picea* may be better suited than *Pinus* to intensive fertilization in sub-boreal and boreal forest regions.

3 Assumes lodgepole pine average wood density is 430 kg/m^3 and wood is 50% carbon.

Aber, J.D., K.J. Nadelhoffer, P. Steudler, and J.M. Melillo. 1989. Nitrogen saturation in northern forest ecosystems. BioScience 39:378–386.

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APPENDIX 1 Fertilization regimes by treatment and year at Sheridan Creek

	Treatment				
Year	**NB**	**NSB**	**Complete**	**ON1**	**ON2**
1993	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K 50S, 25Mg, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B
1994				100N, 100P, 100K, 50S, 25Mg	200N, 100P, 100K, 50S, 25Mg
1995				100N, 100P, 100K, 50S, 25Mg	200N, 100P, 100K, 50S, 25Mg
1996				100N, 100Mg, 17S	200N, 100Mg, 17S
1997				None	None
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N	100N
2000				100N, 50P, 50K, 63S, 32Mg	150N, 50P, 50K, 63S, 32Mg
2001				50N	100N
2002				50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50P, 50K, 50S, 25Mg
2004				75N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn
Total	400N, 3B	400N, 100S, 3B	400N, 200P, 200K, 100S, 50Mg, 3B	825N, 450P, 450K, 333S, 257Mg, 6B, 5Cu, 10Fe, 3.5Zn	1550N, 500P, 500K, 333S, 282Mg, 6B, 5Cu, 10Fe, 3.5Zn

* N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

APPENDIX 2 Fertilization regimes by treatment and year at Kenneth Creek

	Treatment				
Year	NB	NSB	Complete	ON1	ON2
1994	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B
1995				100N, 100P, 100K, 50S, 25Mg	200N, 100P, 100K, 50S, 25Mg
1996				100N, 100Mg, 17S	200N, 100Mg, 17S
1997				None	None
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 50P, 50K, 63S, 32Mg	150N, 50P, 50K, 63S, 32Mg
2001				100N, 10Fe, 3Cu, 2S, 2.5Zn	100N, 50Mg, 10S, 10Fe, 3Cu, 2.5Zn
2002				50N, 1.5B	100N, 1.5B
2003				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
2004				75N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn
2005				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
Total	400N, 3B	400N, 100S, 3B	400N, 200P, 200K, 100S, 50Mg, 3B	825N, 450P, 450K, 335S, 282Mg, 6B, 8Cu, 20Fe, 6Zn	1450N, 450P, 450K, 343S, 332Mg, 6B, 8Cu, 20Fe, 6Zn

* N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

APPENDIX 3 Fertilization regimes by treatment and year at McKendrick Pass

	Treatment				
Year	**NB**	**NSB**	**Complete**	**ON1**	**ON2**
1996	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B
1997				50N, 50P, 50K, 100Mg, 50S	100N, 50P, 50K, 100Mg, 50S
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000				100N, 50K, 63S, 32Mg	150N, 50K, 63S, 32Mg
2001				50N, 50Mg 8S	100N, 100Mg, 17S
2002	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg 1.5B	50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50S
2004				75N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn
2005				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
2006				50N, 50P, 50K, 54S, 25Mg, 10Cu, 10Fe, 6Zn	100N, 50P, 50K, 54S, 25Mg, 10Cu, 10Fe, 6Zn
2007				75N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B
Total	400N, 3B	400N, 100S, 3B	400N, 200P, 200K, 100S, 3B	750N, 450P, 500K, 428S, 332Mg, 7.5B, 15Cu, 20Fe, 9.5Zn	1350N, 450P, 500K, 437S, 382Mg, 7.5B, 15Cu, 20Fe, 9.5Zn

* N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

APPENDIX 4 Fertilization regimes by treatment and year at Tutu Creek

	Treatment				
Year	**NB**	**NSB**	**Complete**	**ON1**	**ON2**
1996	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B
1997				50N, 50P, 50K, 100Mg, 50S	100N, 50P, 50K, 100Mg, 50S
1998				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
1999				50N	100N
2000				100N, 50K, 63S, 32Mg	150N, 50K, 63S, 32Mg
2001				50N	100N, 50Mg, 8S
2002	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N, 1.5B	100N, 1.5B
2003				50N, 50S	100N, 50P, 50K, 50S, 25Mg
2004				75N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn
2005				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
2006				50N, 50P, 50K, 54S, 25Mg, 10Cu, 10Fe, 6Zn	100N, 50P, 50K, 54S, 25Mg, 10Cu, 10Fe, 6Zn
2007				75N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B
Total	400N, 3B	400N, 100S, 3B	400N, 200P, 200K, 100S, 50Mg, 3B	750N, 450P, 500K, 420S, 282Mg, 7.5B, 15Cu, 20Fe, 9.5Zn	1350N, 500P, 550K, 428S, 357Mg, 7.5B, 15Cu, 20Fe, 9.5Zn

* N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

APPENDIX 5 Fertilization regimes by treatment and year at Crater Lake

	Treatment				
Year	**NB**	**NSB**	**Complete**	**ON1**	**ON2**
1997	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 107Mg, 64S, 1.5B	200N, 100P, 100K, 107Mg, 64S, 1.5B
1998				50N, 50P, 50K, 50S, 50Mg	100N, 50P, 50K, 50S, 50Mg
1999				50N, 50P, 50K, 50S, 50Mg, 1.5B	100N, 50P, 50K, 50S, 50Mg, 1.5B
2000				100N, 50K, 63S, 32Mg	150N, 50K, 63S, 32Mg
2001				50N	100N
2002				50N, 1.5B	100N, 1.5B
2003	200N, 1.5B	200N, 50S, 1.5B	200N, 100P, 100K, 50S, 25Mg, 1.5B	50N, 50S	100N, 50S
2004				75N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn	100N, 50P, 50K, 3S, 1.5B, 5Cu, 10Fe, 3.5Zn
2005				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
2006				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
2007				75N, 100P, 100K, 50S, 25Mg, 1.5B	100N, 100P, 100K, 50S, 25Mg, 1.5B
2008				50N, 50P, 50K, 50S, 25Mg	100N, 50P, 50K, 50S, 25Mg
Total	400N, 3B	400N, 100S, 3B	400N, 200P, 200K, 100S, 50Mg, 3B	750N, 500P, 550K, 480S, 339Mg, 7.5B, 5Cu, 10Fe, 3.5Zn	1350N, 500P, 550K, 480S, 339Mg, 7.5B, 5Cu, 10Fe, 3.5Zn

* N, nitrogen; P, phosphorus; K, potassium; S, sulphur; Mg, magnesium; B, boron; Cu, copper; Fe, iron; Zn, zinc. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.